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PEACEFUL NUCLEAR EXPLOSION (PNE) MONITORING TECHNIQUES

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This report presents the results of a preliminary study of techniques, which will aid in reducing the ability of a signatory of a peaceful nuclear explosion (PNE) treaty to use a PNE for illegal purposes, e.g., the testing of nuclear weapons or testing the vulnerability of military systems to nuclear weapons effects. The scope of the study includes investigation of both technical means and appropriate treaty provisions. Ideally, a combination of monitoring techniques, e.g., seismic, EMP, and infrared would be combined

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with selected treaty provisions to provide maximum assurance that covert testing was not being conducted. Theoretical studies involve the development of individual technologies as well as the most effective methods for combining them. In this effort, emphasis has been placed on investigating the feasibility of an electromagnetic pulse (EMP) monitoring system. Such a system may be useful, when used in conjunction with a seismic system, for detecting explosions hidden among one or more declared peaceful explosions.

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SECTION 1
INTRODUCTION

1.1 GENERAL

This report summarizes the work performed by Mission Research Corporation under contract DNA 001-77-C-0252 for the Defense Advanced Research Projects Agency (DARPA) from 23 May 1977 to 31 July 1979 in the area of Peaceful Nuclear Explosion (PNE) treaty verification studies.

1.2 PURPOSE

The possibility of a Peaceful Nuclear Explosion (PNE) Treaty in conjunction with a Comprehensive Test Ban Treaty (CTBT) has posed the question of how one can reduce the possibility of a PNE being used for illegal testing.

The purpose of this study was to initiate an investigation into possible monitoring techniques which could be used under some future form of a PNE treaty (PNET). Emphasis was placed on studying the feasibility of an EMP monitoring network. In addition, the study considers the problem of integrating several types of monitoring systems for efficient coverage of the various possibilities of treaty violation and it considers the problem of formulating a treaty which provides optimum working conditions for the monitoring systems as well as providing conditions which make it difficult to perform illegal tests not easily monitorable.

The study was preliminary in nature. More questions were probably raised than answered. Involved in the study was the collection and review of pertinent PNE literature; examination of current nuclear test procedures; and discussions with personnel connected with on-going treaty negotiations. Many of the points raised in this study are already being addressed by the appropriate people and we do not wish to imply otherwise or to belittle their efforts. The authors have developed a great respect for the problems of treaty negotiation and for the people who must wrestle with those problems. Our contribution lies more in the difference of our viewpoint. We are technically oriented, and oriented in a way that differs from the personnel who have always been associated with test ban treaties. Going into this study, we knew nothing of seismic techniques, the mainstay of past treaty monitoring systems. For that reason we were possibly a little more open, a little more naive, perhaps, in our approach to the problem. We feel that was good. Of course, we have our prejudices also, which is what led to the reopening of the question of using EMP to monitor nuclear explosions.

What can one expect to gain by monitoring a PNE? Ideally, one might hope to prevent the following four achievements by the party conducting the explosion:

1. Development and testing of new weapons designs
2. Testing of stockpiled weapons
3. Testing the nuclear hardness of equipment designed to operate in a nuclear environment
4. Performing experiments designed to increase knowledge of the nuclear environment.

Clearly, it will be impossible to prevent a PNE from being used for other than peaceful purposes without total control over the explosive and over the site of the explosion. However, it is possible to make

difficult the illegal use of a PNE through the wise choice of controls and monitoring techniques and, what is just as important, it is possible to predict the risks involved before treaty negotiation. Various combinations of treaty controls and monitoring techniques can be developed and evaluated as to their effectiveness in preventing the four categories of treaty violation listed above. These combinations can be negotiated as packages, with the most effective packages being proposed first and with less intrusive (and effective) packages being retained as fall-back positions.

There are three general categories of PNE monitoring:

1. Explosive canister monitoring
2. Site monitoring
3. Explosion emissions monitoring.

These are discussed in more detail in Section 5. Explosive canister monitoring is used to gain some knowledge about the explosive design and about the diagnostics package attached to the explosive. A treaty might impose certain restrictions on the explosive and diagnostics canisters which would inhibit the usefulness of the explosion as a weapons test and these restrictions would be easily monitorable.

Site monitoring would be used to detect unauthorized activity or underground structures or objects which would indicate the existence of an unauthorized test or experiment. For example, one might look for concealed chambers, cable runs, or equipment.

The various electromagnetic and acoustic emissions from the burst could also be monitored for the same purpose. One may try to detect the existence of an extra unauthorized explosion, for example. Such an explosion would initiate an illegal weapons test.

1.3 REPORT ORGANIZATION

This report is issued in two parts. The first part contains the bulk of the study. Part 2 contains certain details which were not considered suitable for general distribution.

Section 2 of Part 1 contains background information concerning the status of the various test ban treaties and a general description of nuclear testing. Section 3 describes several nuclear test monitoring techniques, some of which are proven and others which are still being studied. Section 4 discusses the idea of an EMP monitoring network. Section 5 places forth some of our ideas on treaty strategoy and monitoring systems integration. Section 6 contains our recommendations for future work.

SECTION 2
HISTORY AND BACKGROUND

2.1 INTRODUCTION

In order to approach the nuclear explosion monitoring problem from a technical point of view, it is useful to have some perspective on the past and on the broader issues involved. This section summarizes some of the non-technical historical and background aspects involved in the PNE monitoring study. For more details it is suggested that the reader consult References 1 and 2 which provide a comprehensive and up-to-date treatment of PNE's and current monitoring techniques.

Subsection 2.2 contains a brief discussion of the various treaties and negotiations between the United States and the Soviet Union from 1958 until the present time that pertain to nuclear explosions. The full texts of the treaties are contained in References 1 and 3.

The constraints imposed by the various agreements have had a strong influence on the nuclear explosion activities of both countries. These are broken down into two catagories, military and peaceful programs. The military nuclear explosion programs which include weapon development and weapon effects tests are summarized in Subsection 2.3.

Subsection 2.4 describes the PNE programs of both countries, with a summary of the U.S. Plowshares program and a review of Soviet projects up to 1975. Details on the various projects are given in Reference 2.

Subsection 2.5 reviews the background and status of existing verification programs with emphasis on seismic methods of nuclear explosion detection as discussed in detail in Reference 1.

2.2 NUCLEAR TEST BAN TREATIES AND NEGOTIATIONS

2.2.1 General

There are currently four main types of treaties either in effect, negotiated, or being negotiated by the United States and the Soviet Union concerning nuclear testing.* They are; the Limited Test Ban Treaty (LTBT) of 1963, which prohibits above ground tests; the Threshold Test Ban Treaty (TTBT) of 1974, which limits the yield and number of underground tests, which has not been ratified by Congress; the Peaceful Nuclear Explosion Treaty (PNET) of 1976, which has not been ratified by Congress; and a Comprehensive Test Ban Treaty (CTBT) under negotiation. These are summarized in Section 2.2.2 which is taken from Reference 3.

The latest development in the nuclear test ban scene was a speech by Soviet Leader Leonid Brezhnev on the Soviet Union's 60th anniversity of November 1977, in which he proposed a moratorium on all nuclear explosions, peaceful as well as military, and a gradual destruction of atomic weapon stockpiles. This is discussed at some length in Reference 4. The implications of the Soviet proposal on current CTBT negotiations and the TTBT and PNET ratifications are unclear at this time.

2.2.2 Summary of Test Ban Activities

The Limited Test Ban Treaty

The first proposal for stopping nuclear weapon tests was made in 1955, and the first major negotiations with the Soviet Union for an

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* Related treaties include: The Antartic Treaty; The Outerspace Treaty; The Non-Proliferation Treaty; The Treaty of Tlatelolco; and The Sea Bed Treaty (see Reference 1 for details).

effectively controlled test ban began in Geneva in 1958, with the United Kingdom also participating. The Conference on the Discontinuance of Nuclear Weapons Tests produced no agreement. The problem of working out verification procedures to insure compliance with a complete ban on nuclear weapon tests in all environments proved to be intractable at that time. The procedures deemed necessary by the United States and the United Kingdom were not acceptable to the Soviet Union.

In 1963 the Limited Test Ban Treaty (LTBT) was signed by the Soviet Union, the United States, and the United Kingdom. This treaty prohibits nuclear weapon testing in the atmosphere, in outer space and under water. The parties also agreed not to carry out any nuclear weapon test, or any other nuclear explosion, in any other environment, i.e., underground—that would cause radioactive debris to be present beyond the borders of the country in which the explosion took place.

Underground nuclear explosions were not prohibited by the 1963 treaty, although both in the treaty preamble and Article I, the LTBT parties pledged to seek "the discontinuance of all test explosions of nuclear weapons for all time...."

It is not possible in many cases to distinguish between the seismic signals caused by an underground nuclear explosion and those caused by an earthquake. The United States has conducted extensive research in an effort to solve this problem—an investment of over $300 million over the past decade. But, despite substantial advances in seismic technology, the U.S. Government continues to believe that some on-site inspection would be necessary to supplement long-range seismic data. The Soviet Union has consistently taken the position that no on-site inspection is needed to verify a comprehensive test ban.

Taking into account this longstanding impasse, the United States and the Soviet Union agreed in the spring of 1974 to pursue the possibilities of further partial restrictions on nuclear weapon testing. Accordingly, a team of U.S. experts was sent to Moscow for technical talks.

The Threshold Test Ban Treaty

Agreement on the Treaty on the Limitation of Underground Nuclear Weapon Tests, also known as the Threshold Test Ban Treaty (TTBT), was reached during the summit meeting in Moscow and signed in July 1974. Ratification was not sought, however, because that Treaty would have been incomplete without a Treaty on Underground Nuclear Explosions for Peaceful Purposes.

The treaty limiting weapons testing establishes a nuclear "threshold," prohibiting tests having a yield exceeding 150 kilotons. The parallel treaty on peaceful nuclear explosions (PNE's) places exactly the same limit of 150 kilotons on the yield of any individual nuclear explosion for peaceful purposes, such as might be conducted as part of an engineering project.

This is because at the time the Threshold Test Ban Treaty was concluded, the two parties recognized the need to establish an appropriate companion treaty to govern peaceful nuclear explosions, since there is no essential distinction between the technology of a nuclear explosive device that could be used as a weapon and a nuclear explosive device used for a peaceful purpose. Article III of the Threshold Test Ban Treaty specifically excluded PNEs from its provisions and called for negotiation of a separate treaty to govern them (see PNE Treaty).

The TTBT includes a protocol which details technical data to be exchanged and which limits weapon testing to specific designated test sites to assist verification. The data to be exchanged include information on

the geographical boundaries and geology of the testing areas. Geological data—including such factors as density of rock formation, water saturation, and depth of the water table—are useful in verifying test yields because the seismic signal produced by a given underground nuclear explosion varies with these factors at the test location. After an actual test has taken place, the geographic coordinates of the test location are to be furnished to the other party, to help in placing the test in the proper geological setting and thus in assessing the yield. Other information available to the United States will be used to cross check the data provided.

The treaty also stipulates that data will be exchanged on a certain number of "calibration tests." By establishing the correlation between stated yields of explosions at the specified sites and the seismic signals produced, this exchange will help improve assessments by both parties of the yields of explosions based primarily on the measurements derived from their seismic instruments. The tests used for calibration purposes may be tests which have been conducted in the past or may be new tests.

Agreement to exchange the detailed data described above represents a significant degree of direct cooperation by the two major nuclear powers in the effort to control nuclear weapons. For the first time, each party will make available to the other data relating to its nuclear weapons test program.

The mutual restraint undertaken in the Threshold Test Ban Treaty will significantly reduce the explosive force of new nuclear warheads and bombs which could otherwise be developed for weapon systems. Of particular significance is the relationship between explosive power of reliable, tested warheads and first-strike capability.

The Threshold Test Ban Treaty contains a formal commitment by the parties to continue negotiations with a view toward achieving a solution to the problem of the cessation of all underground weapon tests. If a comprehensive test ban treaty can be achieved, such a treaty would replace the threshold ban.

The PNE Treaty

Negotiations on a PNE treaty began in Moscow on October 7, 1974. The U.S. delegation was headed by Ambassador Walter J. Stoessel, Jr., U.S. Ambassador to the Soviet Union, and included experts from the Arms Control and Disarmament Agency, the Department of State, the Office of the Secretary of Defense, the Joint Chiefs of Staff, and the Energy Research and Development Administration. The talks, involving subject matter of great technical complexity, took place in six rounds during a period of 18 months. They resulted, in early April of 1976, in the Treaty on Underground Nuclear Explosions for Peaceful Purposes.

Both the United States and the Soviet Union have had research, development, and testing programs for PNE's for many years (see Section 2.4). Work in the United States to date has failed to establish any applications which appear to be both technically feasible and economically viable. The United States has not carried out any PNE experiments for several years and has no present plans to conduct any such experiments. The Soviet Union, however, has continued a research, development, and testing program for PNE

The United States pursued three basic objectives in participating in the PNE negotiations:

- PNE's must not provide weapon-related benefits otherwise precluded by the Threshold Test Ban Treaty.
- The fact that PNE activities are not contributing such benefits must be adequately verifiable.
- The PNE Treaty must be consistent with existing treaty obligations including in particular the Limited Test Ban Treaty of 1963.

The PNE Treaty signed with the Soviet Union fulfills these objectives. Specifically, the two nations have agreed not to carry out any individual peaceful nuclear explosion having a yield exceeding 150 kilotons, not to carry out any group explosion (consisting of a number of individual explosions) with an aggregate yield exceeding 1500 kilotons and have reaffirmed their intention to comply fully with the Limited Test Ban Treaty.

The PNE Treaty will govern all nuclear explosions carried out at locations outside the weapon test sites specified under the Threshold Test Ban Treaty.

The parties reserve the right to carry out peaceful nuclear explosions in the territory of another country if requested to do so, but only in full accord with the yield limits and other conditions of the treaty. This provision is consistent with the article in the Non-Proliferation Treaty of 1970 regarding the availability of benefits of PNE's to countries that foreswear a nuclear weapons capability. In this regard, appropriate assistance to the International Atomic Energy Agency is pledged.

Articles IV and V of the PNE Treaty cover the agreed verification arrangements. In addition to the use of national technical means--and the commitment not to interfere with the national technical means of the other party—the treaty provides that information and access to sites of explosions will be furnished by each side. The permitting of onsite access by observers is a landmark in U.S.-Soviet cooperation in implementing agreements concerned with nuclear arms control.

A Joint Consultative Commission will be established to discuss any questions of compliance, to develop further specific details of the on-site inspection process as needed, and to facilitate cooperation in various areas related to PNE's which might be mutually beneficial.

The Protocol to the PNE Treaty sets forth the specific operational arrangements agreed to for making sure that no weapon-related benefits precluded by the Threshold Test Ban Treaty are derived by carrying out a peaceful nuclear explosion.

The central problem to be solved through these procedures is that of insuring that no single nuclear device will be exploded with a yield exceeding 150 kilotons. Special procedures are required when the aggregate yield of group explosions is larger than 150 kilotons, because seismic instruments located far distant from the site of a group explosion would only register the total yield of the entire group. It is necessary, therefore, to have observers and instruments at the site of a group explosion to determine the yield of each of the individual devices making up the group explosion. In addition, observers may be permitted on the basis of consultation between the parties, for explosions with aggregate yields between 100 and 150 kilotons.

As an example of the procedures agreed upon and set forth in the Protocol to the Treaty, American observers will have the right to place instruments down into the emplacement hole containing each nuclear explosive device for any Soviet PNE with an aggregate yield above 150 kilotons in order to measure the yield of the explosion of each device. One kind of such instrument is called a SLIFER, an acronym that stands for Shorted Location Indication by Frequency of Electrical Resonance. It measures the yield of the explosion by measuring the speed of the hydrodynamic shock wave that travels outward from the center of the explosion.

In addition to this guaranteed access for observers at group explosions whose aggregate yield exceeds the 150 kiloton threshold, an arrangement the Soviet Union has never before agreed to, the PNE Treaty requires extensive amounts of information to be provided about a PNE of any yield, before and after the explosion.

At the present time, there exists a standing PNE observer team equipped to move on-site under the provisions of the current draft treaty. The team is under the control of ERDA and includes translators and medical personnel as well as technicians. Equipment and clothing are available for operation in cold climates. Some research is being performed on advanced procedures which will be compatable with the present treaty provisions, e.g., advanced SLIFER systems. Organizations involved are ERDA (Nevada Operations Office), Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory, Sandia Corporation, EG&G Corporation, and the U.S. Geological Survey.

Both the TTBT and the PNET are designed to remain in force for a period of five years, and will be extended for successive five year periods unless either party wishes to terminate them.

The article in the Treaty on Peaceful Nuclear Explosions relating to duration specifies that "under no circumstances shall either Party be entitled to terminate this Treaty while the Treaty on the Limitation of Underground Nuclear Weapon Tests remains in force."

The Comprehensive Test Ban Treaty

The task of devising an acceptable treaty to terminate all nuclear weapons testing remains on the agenda of the U. S. Government, and, in Article I, the parties to the Threshold Test Ban Treaty undertook an obligation to continue negotiations toward that goal. That task of reaching an agreement to terminate all nuclear weapon tests includes two critical questions that are still beyond the scope of the present TTB and PNE treaties: (1) whether a regime for PNEs can be found that would be consistent with a complete ban on nuclear weapon tests, and (2) arrangements to provide for adequate verification.

The announcement of Brezhnev of November 1, 1977, that the Soviet Union is prepared to reach an agreement on a moratorium covering

nuclear explosions for peaceful purposes as well as all nuclear weapons tests for a definite period raises new questions regarding verification which are beyond those of the PNE Treaty.

2.3 MILITARY NUCLEAR EXPLOSION PROGRAMS

2.3.1 General

The difference between a nuclear explosion used for war and one used for peaceful purposes is primarily a matter of design application. The basic phenomenology and effects of the various types of nuclear explosions have been documented in a number of publications such as References 5 and 6 and the information is readily available.

Nuclear weapons, however, are designed for specific military applications and information on both the design features of various types of warheads and their nuclear effects on military systems is largely classified. The knowledge needed to assess the effectiveness of a country's nuclear ordnance is obtained primarily through nuclear weapons test programs. Such test programs consist of dual components: weapon development tests and nuclear effects tests.

As discussed in Section 2.2, the United States and the Soviet Union are confined through the Limited Test Ban Treaty of 1963 to the use of underground tests (UGT's) for both military and peaceful applications.

2.3.2 Underground Weapons Tests

As opposed to tests on and above the earth's surfaces such as those conducted by the United States and the Soviets prior to 1963 and the French and communist China today, underground tests must be contained in tunnels and cavities well below the surface of the earth. Figure 2-1 shows the configuration for a typical weapons effects UGT at N.T.S.

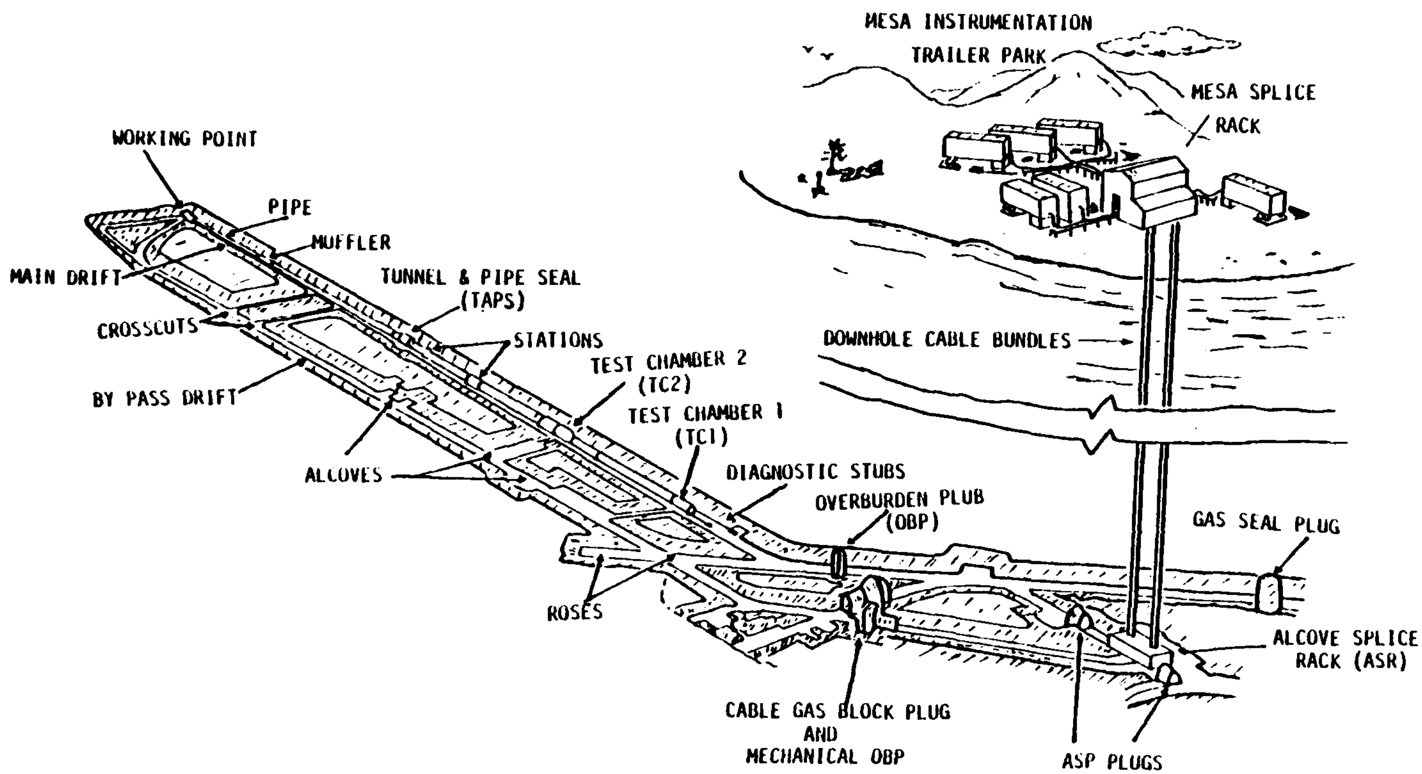

Figure 2-1. Typical UGT configuration

Weapons developments tests do not require such an elaborate configuration in that they basically consist of a diagnostic canister designed to measure the output of the device. Both weapons development and weapons effects experiments are fielded together on many UGTS. A detailed discussion of UGT procedures is presented in Section 4.

2.3.3 Weapons Development Programs

Nuclear weapons development programs are many faceted, encompassing everything from materials research to development of production techniques. The nuclear tests are only a part of the program. However, they are vital to the development process in that they are the only proof that design goals have or have not been met. Some considerations in a specific program in addition to the device itself are the size, shape, and center of gravity of the warhead, timing, fusing and firing mechanism and interfaces with the other components of the system. The range of weapon designs in terms of yields, sizes, and shapes may vary from large multi-megaton warheads carried by ICBM's and aircraft to small subkiloton artillary projectiles. The current trend in both U.S. and Soviet weaponry is the multiple independently targetable reentry vehicles (MIRV's) which use kiloton range yield devices in highly sophisticated nuclear warheads.

In the United States nuclear weapon development programs are the responsibility of a branch of the Energy Research and Development Agency (ERDA), formerly the AEC. The budget in FY 1978 for nuclear weapons development activities was about 1.45 billion dollars. Of this approximately 260 million was earmarked for UGTs. Of the remainder about 440 million was for R&D and 750 million for production. Research and development and testing activities were aimed at developing new warheads for the Cruise Missile, the MX Mobile Missile and the Trident 2 Submarine Missile. Production activities included nine proven designs including: the Full Fusing Option Strategic Bomb to be delivered by an aircraft such

as the B1 or FB-111; an enhanced radiation warhead for the LANCE surface to surface missile; the W80 warhead for the short range attack missile (SCRAM B) or the Cruise Missile; the W76 warhead for the Trident 1 missile; the MK12 warhead for MM III; three types of Tactical Nuclear Bombs; and an 8-inch artillary fired projectile.

It is assumed that the Soviets have a similar program, covering a competitive range of weapons. Monitored Soviet test activities over the past two years have included a number of explosions in the 150-250 KT range and greater in locations (Novaya Zemlya) generally reserved for warhead tests. Such tests would be needed for development of weapons for the new family of Soviet ICBM's, SS16, 17, 18 and 19, which have MIRV capabilities. Small yield weapons for tactical applications could have been tested without our knowledge. Current detection capabilities outside the Soviet Union are limited to approximately 10-15 Kilotons if tests are conducted in hard rock. In softer soils tests five times that size could be performed without detection (according to Reference 4).

2.3.4 Weapons Effects Programs

Underground nuclear tests are one of the ways to obtain data on the survivability/vulnerability of military equipment in a nuclear environment. In the U.S. UGT's in consonance with non-nuclear simulators and theoretical calculations (large computer codes) have been used effectively to predict the response of various materials, components sub-systems and systems to the effects of nuclear radiation.

In this country the planning and fielding of nuclear weapons effects UGT experiments is one of the responsibilities of the Defense Nuclear Agency (DNA) formerly the Defense Atomic Support Agency (DASA). The FY 1978 DNA Budget for UGT's was 38.5 million dollars. The tests are conducted in coordination with ERDA and over the past five years have

been used to expose a wide variety of military hardware to determine the effects of X rays, gammas, neutrons, transient radiation, and electromagnetic pulse.

It is assumed that the Soviets have a counterpart weapon effects program in which UGTs are used for system s/v analyses. Indications have been received that they have an active, non-nuclear weapons effects simulation program and have developed, or borrowed theoretical techniques which can be applied to weapons effects problems. The extent of their interest in UGT weapons effects tests is speculative

2.4 PEACEFUL NUCLEAR EXPLOSION PROGRAMS

2.4.1 General

Once it was realized that there was a good probability of developing a nuclear explosive device, there were speculations on possible peacetime utilization of these explosives. However, it was not until the late 1950's that a program on Peaceful Nuclear Explosions (PNE) actually commenced at the Lawrence Livermore Laboratory (LLL) of the University of California. Soon named the Plowshare Program, this effort received wide publicity and its findings were watched with interest throughout the world. The U.S.S.R. started a comparable program in the early 1960's, a program that, in recent years, has involved more PNE testing than that of the U.S., see Subsection 2.4.3. Since then, other nations have become involved. A few have made explicit studies of ways in which they might use Peaceful Nuclear Explosions (PNE), and there have been a few underground weapons tests by the French which have supplied additional phenomenological data to those of the U.S. and the U.S.S.R. There has been some activity of the Republic of India which exploded a nuclear device underground in the Rajasthan Desert in 1974 and announced that this was the beginning of a broad program on PNE's.

2.4.2 The U.S. PNE Program

Project Plowshare (now the PNE Program) was established by the AEC in 1957 to investigate the non-military applications of the nuclear explosives and, throughout the life of this effort, the AEC (now ERDA) has been the leading U.S. agency. Other U.S. government agencies, e.g., the Corps of Engineers, have cooperated and some of the applications tests have had participation from industry, but the large fraction of the support has come from the AEC. Details of the U.S. PNE program can be found in References 6 and 7.

Over the nearly two decades to 1975, the total AEC funding for Project Plowshare was about $160 million.* About two-thirds of this was for experiments which were oriented toward earth-moving, e.g., cratering experiments; the other third went to various kinds of contained applications, e.g., stimulation of natural gas production. Although the Plowshare effort has been unclassified, with open publication of results and much international discussion, the interplay between the U.S. nuclear weapons test program has been close. Many of the tests which were important to Plowshare were carried out at the Nevada weapons test site, and much of the information gathered in the weapons test program had relevance to Plowshare activities. For example, the scaling law which determines how deep a given explosion must be in order to be contained is based on data from weapons tests as well as from Plowshare tests.

The Plowshare program was multi-faceted. There were detailed analyses and numerous experimental studies of a variety of non-military applications to which PNE's might contribute. However, the heart of the program was the group of field tests which were carried out to determine more carefully the characteristics of nuclear explosions as applied to

* The name Plowshare fell into official disuse after 1970 or 1971, being replaced by PNE.

various non-military applications. ERDA lists eleven Plowshare field tests, dating from the 1961 Gnome test in New Mexico, to the 1973 Rio Blanco test in Colorado. In addition, ERDA lists as part of the Plowshare program fifteen explosives development experiments, and two special experiments on explosives emplacement. Finally, ERDA points to an additional 21 non-Plowshare tests with Plowshare participation, or which contributed to Plowshare technology.

Only three of these Plowshare tests involved the study of a particular application, the stimulation of production of natural gas. The three tests, all of which involved government-industry collaboration and funding, were: Gasbuggy in 1967, Rulison in 1969, and Rio Blanco in 1973 (the first in New Mexico and the latter two in Colorado).

The initial public response to Project Plowshare was positive. The idea of converting nuclear swords into plowshares was attractive, and so were many of the early projections of large savings of time and money by using PNE's to build, for example, a sea level alternative to the Panama Canal. Later and more detailed analyses dampened the enthusiasm somewhat by pointing to the inescapable side effects of many of these projects. However, it was not until the 1969 and 1973 Rulison and Rio Blanco tests in Colorado that public opposition to Plowshare field tests became vigorous and directed. Homeowners and ranchers near the sites of the two Colorado PNE tests were concerned about impact on their property and businesses, but more vehement opposition came from nationwide environmental protection groups concerned about the impact of radioactivity both at the site and in the product gas. Although both tests were ultimately carried out, the negative public response was sobering, especially for the industrial companies involved. Concern in Colorado remained high and ultimately led to an amendment to the Colorado constitution requiring that no nuclear explosions be carried out within the state without voter approval by means of a statewide referendum.

Uncertainty about the utility of PNE's has also been reflected in Congressional reaction. The 1975 Energy R&D Appropriation Act carried a provision that none of the funds shall be spent for "field testing of nuclear explosives in the recovery of oil and gas." Furthermore, the proposed FY 1976 budget of the AEC successor, ERDA, apparently did not contain any explicit line item for PNE activities. Instead, the focus was on end-use efforts, e.g., recovery of oil from shale, to which PNEs may or may not contribute.

2.4.3 The Soviet PNE Program

In contrast to the U.S. PNE program the Soviet Union has had an active PNE program since 1964 and have tentative plans to continue and expand their activities. In fact one of the reasons for the PNE treaty was to satisfy the Soviet's desire to carry out PNE's as a part of their national economy plans. The recent proposal for a Comprehensive Test Ban Treaty to halt all nuclear explosions for some definite period indicates a willingness to abandon their previously stated plans.

A review of Soviet data on the peaceful uses of nuclear explosions up to 1975 is contained in Reference 8 from which Tables 2-1 through 2-3 and Figure 2-2 have been extracted. The information in Reference 8 is a summary of Soviet presentations at a series of meetings sponsored by the International Atomic Energy Agency and a number of papers published in the open literature. In Tables 2-1 and 2-2 the applications have been broken down into excavation projects and contained explosions such as those used for oil and gas stimulation. The most ambitious project in the Soviet PNE program is the planned Pechora-Kama Canal project which is aimed at diverting the flow of the upper portion of the Pechora River, which now flows to the Barents Sea, into the Kama River which flows into the Volga River and the Caspian Sea. The northern 65 km of the proposed 112 km canal is being considered for construction by the use of about 250 explosives with up to 20 explosions in a salvo and salvo yields up to 3 MT.

Table 2-1. Soviet excavation PNE applications.

Application	Explosives	Comments
Water Resource Development:		
1003	1·1 kt	Cratering shot in siltstone.
1004	125 kt	Crater in river produced two lakes, 1·6 x 10^7 m^3 (13,000 acre-ft) "Proven Technology".
Proposed reservoir	Two 150-kt	To form 3 x 10^7 m^3 (24,000 acre-ft) reservoir.
T-1	0·2 kt	Cratering shot in sandstone calibration for T-2.
T-2	Three 0·2-kt	Row-charge cratering shot "model of Pechora-Kama".
Proposed Pechora-Kama Canal	250 explosives	Divert Pechora River into Kama River and thence to Caspian Sea.
Pechora-Kama row crater	Three 15-kt	Experiment at southern end of Pechora-Kama Canal alignment to gain data on cratering characteristics and stability in saturated, alluvial medium.
Overburden Removal:		
Proposed mining project	-1-Mt row charge	Will remove 900,000 m^3 of overburden at 5 kopeks/m^3

Table 2-2. Soviet contained PNE applications.

Application	Explosives	Comments
Control of Runaway Wells:		
Urtabulak	30 kt	$75 million lost over 3 years
Nearby gas field	40 kt	"Proven Technology"
Oil Stimulation:		
Field A	Two 2·3-kt + one 8-kt	28% internal rate of return in U.S.
Field B	Two 8 kt	"Proven Technology"
Proposed Field C	Three 20-30 kt	Designed to break barrier so underlying water will push oil out
Gas Stimulation:		
Undescribed	-	Statement that such an application was carried out
Proposed gas condensate field	Three 40-kt	Expect increase from 7·5 x 10^6 to 100 x 10^6 ft^3/day
Underground Storage of Oil or Gas:		
Salt Dome A	1·1 kt	Salt dome - leaked water and radioactivity
Salt Dome B	25 kt	10^6-bbl storage at 1/6 surface gas storage and 1/3 washed cavities cost
Unidentified cavity	-	Tested with oil and gas at 6 MPa (60 atm)
Gas condensate storage facility	15 kt	300,000-bbl storage facility in industrial use at a gas condensate deposit -- working pressure 8 MPa (80 atm)
Proposed - layered salt	Two 35-kt	Require 2 x 10^6-bbl storage for gas condensate
Proposed - tuff under permafrost	Three 40-kt	Require 2·5 x 10^9 ft^3 storage for gas at 7 MPa (70 atm)
Mineral Development:		
"Granddaddy Shot"	1 kt	Granite shot similar to Hardhat
Proposed ore breaking	2·8 kt	Will break ~10^6 m^3 of ore in situ

Table 2-3. Presumed nuclear events in the Soviet Union occurring away from normal test sites.

	NEIS[a] or SIPRI[b] data						Event identified as presumed explosion by:		
Ident. Number	Date	Origin time (GMT)	Lat °N	Long °E	Magnitude M_b	Depth (km)	SIPRI	USAEC	Location
1	65-01-15	05:59:59	49.89	78.97	6.0	0	No	Yes	Semipalatinsk area[c]
2	66-04-22	02:58:04	47.86	47.72	4.9	0	Yes	No	North of Caspian
3	66-09-30	05:59:53	38.8	64.5	5.1	33	Yes	No	Bukhara
4	67-10-06	07:00:03	57.69	65.27	4.7	N	Yes	No	East of Urals
5	68-05-21	03:59:12	38.916	65.159	5.4	13	Yes	No	Bukhara
6	68-07-01	04:02:02	47.922	47.950	5.5	N	Yes	Yes	North of Caspian
7	69-09-02	04:59:57	57.415	54.860	4.9	0	Yes	No	Urals Region
8	69-09-08	04:59:56	57.365	55.108	4.9	0	Yes	Yes	Urals Region
9	69-09-26	06:59:56	45.890	42.472	5.6	0	Yes	Yes	West of Caspian
10	69-12-06	07:02:57	43.832	54.783	5.8	0	Yes	Yes	East of Caspian
11	70-06-25	04:59:52	52.201	55.692	4.9	0	Yes	No	North of Caspian
12	70-12-12	07:00:57	43.851	54.774	6.1	0	Yes	Yes	Caspian Region
13	70-12-23	07:00:57	43.827	54.846	6.1	0	Yes	Yes	Caspian Region
14	71-03-23	06:59:56	61.287	56.466	5.6	0	Yes	Yes	Northern Urals
15	71-07-10	16:59:59	64.168	55.183	5.3	0	Yes	Yes	W. Slope of Urals
16	71-09-19	11:00:07	57.777	41.098	4.5	N	Yes	No	Urals Region
17	71-10-04	10:00:03	61.613	47.116	5.1	13 ± 29	Yes	No	Western Russia
18	71-10-22	05:00:00	51.575	54.336	5.3	6 ± 18	Yes	Yes	Southern Urals
19	71-12-22	06:59:56	47.872	48.222	6.0	0	Yes	Yes	North of Caspian
20	72-07-09	—	49.9	35.2	5.0	—	Yes	No	North of Black Sea
21	72-07-14	—	55.8	47.4	3.5	—	Yes	No	North of Caspian
22	72-08-20	02:59:58	49.462	48.179	5.7	0	Yes	Yes	North of Caspian
23	72-09-04	07:00:04	67.689	33.445	4.6	7 ± 30	Yes	No	Western Russia
24	72-09-21	09:00:01	52.127	51.994	5.1	28 ± 19	Yes	Yes	Southern Urals
25	72-10-03	08:59:58	46.848	45.010	5.8	0	Yes	Yes	Northwest of Caspian
26	72-11-24	09:00:08	52.779	51.067	4.7	N	Yes	No	Western Russia
27	72-11-24	09:59:58	51.843	64.152	5.2	0	No	Yes	Southeastern Urals
28	73-08-15	01:59:58	42.711	67.410	5.3	0	d	Yes	Northwest of Tashkent
29	73-08-28	02:59:58	50.550	68.395	5.3	0	d	Yes	N. Kazakh Desert
30	73-09-19	02:59:57	45.635	67.850	5.2	0	d	Yes	C. Kazakh Desert
31	73-09-30	04:59:57	51:608	54.582	5.2	0	d	Yes	Southern Urals
32	73-10-26	05:59:58	53.656	55.375	4.8	0	d	Yes	Southern Urals

[a]NEIS = National Earthquake *Information* Service (formerly NOAA and USC&GS).

[b]SIPRI = Stockholm International Peace Research Institute.

[c]This event was near the Semipalatinsk testing area but fell well outside the area of all previous Soviet events at the time it occurred. Significant amounts of atmospheric radioactivity were reported in association with this event leading to speculation that it was a PNE nuclear cratering event.

[d]Date of event is after publication of SIPRI report.

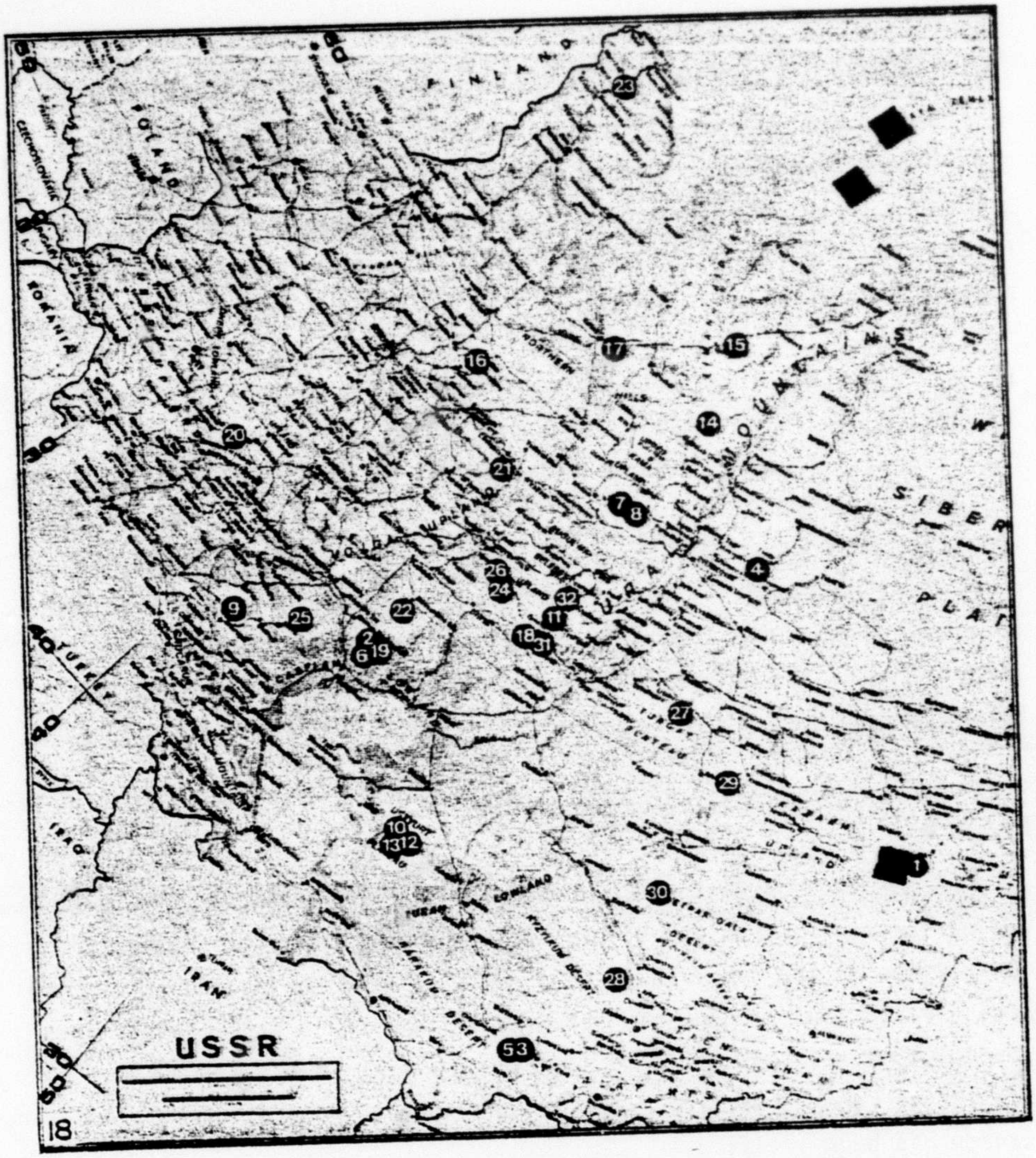

Figure 2-2. General locations of presumed nuclear events located away from the normal weapons-test sites at Semipalatinsk and Novaya Zemlya (shown by squares).

In addition to the 16 events reported openly by the Soviets a number of other nuclear explosions outside the nuclear test areas of Novaya Zemlya and Semipalatinsk were detected by seismic means. These are listed in Table 2-3; the general locations of these events are shown on Figure 2-2, the squares represent the Novaya Zemlya and Semipalatinsk nuclear test areas.

As indicated in Tables 2-1 and 2-2 the Soviets have described in varying detail 16 nuclear explosions which have contributed to their PNE program. Seismic evidence presented in Table 2-3 and Figure 2-2 would indicate 32 events, including six in 1971, eight in 1972, and five in 1973 through November 1, 1973. It thus appears that the Soviets have carried out at least 17 PNE events in addition to those described and that they accelerated their PNE program in the later years. Additional information on the Soviet PNE program through 1976 is contained in Reference 1.

2.5 EXISTING MONITORING PROGRAMS

Since the beginning of negotiations on nuclear explosion treaties one of the major stumbling blocks has been the problem of verifying that the parties to the treaty have in no way violated the agreements. Until recently the Soviet Union has steadfastly refused to agree to any form of on-site inspection and although the draft PNE treaty has such provisions (see Subsection 2.2) they will not become effective until the treaty has been ratified.

Until that time as in the past the monitoring of nuclear explosions by the United States and the Soviet Union must be performed remotely. The U.S. program for remote detection of nuclear explosions consists of satellites which contain various sensors and cameras for obtaining evidence of nuclear detonations and seismic arrays designed to monitor underground explosions along with earthquakes.

As mentioned earlier, it has been sometimes difficult to distinguish the seismic signals produced by a nuclear explosion and those caused by an earthquake. Although considerable research has been devoted to this problem during the past decade[9,10] there are still limitations on the effectiveness of seismic verification. Because of this there is concern that a country wishing to hide nuclear explosions could do so by masking them in earthquakes or simulating earthquakes.[11,12] Other methods of concealing nuclear explosions from seismic detection such as using large cavities[13] or low yield detonations in soft soil[1] are also possible.

All told, according to Reference 1 there were 1116 seismic stations in operation in 1974 throughout the world with at least short period, but often also long period seismometers and photograph recording equipment. Included in this number are the worldwide standard stations network (WWSSN)* which number approximately 125 and are more or less identical. There are several other network systems including a western U.S. network system including about 180 stations and a southwestern U.S.S.R. network consisting of about 70 stations, which in some cases are part of the WWSSN. The WWSSN and most other conventional seismic stations are useful for detecting local earthquakes and signals from fairly strong distant earthquakes but are limited in value in detecting weak explosions.

In an effort to improve underground nuclear explosion monitoring capabilities a number of array stations with varying numbers and types of short and long period seismometers have been installed in selected locations throughout the world. The three major arrays used by the U.S. are: the Large Aperture Seismic Array (LASA) in southeastern Montana, containing about 345 short-period and 17 three-component, long-period instruments; the Norwegian Seismic Array (NORSAR) in southern Norway, containing

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* Sometimes referred to as the Worldwide Standardized Seismograph Network.

about 132 short-period and 22 three-component long-period instruments; and Alaskan Long-Period Array (ALPA) in central Alaska, containing 19 three-component, long-period seismometers. In addition to the arrays there are a number of Seismic Research Observatories (SRO) and several Very Long Period Experiment Stations (VLPES) in the system. Data from the arrays and the other recording stations are now transmitted through ARPANET, a computer communication network consisting of high-speed transmission lines and satellite links to the Seismic Data Analysis Center in Arlington, Virginia where they are recorded and studied.

Improvements in measurement techniques and data analysis are continuing that will be useful in a number of areas of seismological research. Whether seismic technology can be advanced to the point where it will be accepted, even with other remote techniques such as sophisticated reconnaissance satellites as a substitute for on-site verification techniques is uncertain at this time. Several proposals have been made on verifying a comprehensive test ban treaty[1] which rely heavily on improved seismic networks and an international seismic data center as part of a monitoring system.

SECTION 3
PNE MONITORING TECHNIQUES

3.1 INTRODUCTION

Unlike other treaties and negotiations on nuclear explosions which limit monitoring activities to the use of remote techniques such as seismic networks and reconnaissance satellites, the PNE Treaty (see Subsection 2.2) allows for on-site inspections and observations. It also permits measurements at the site for PNE's with aggregate yields exceeding 150 kilotons, to determine the yield of each individual explosion and possibly ensure that the explosions are not used for military purposes.

In this section, we discuss several techniques which may be applicable to the problem of monitoring a peaceful nuclear explosion. Some of these, such as SLIFER and radiochemistry, are state of the art and are presently used in weapons tests. Others are in the research or speculation stage.

One particular technique, electromagnetic pulse, was of special concern in these studies. It is discussed in Section 4.

Monitoring techniques cannot be depended upon alone to aid in reducing the feasibility of using a PNE for illegal testing. Technical procedures can be aided by treaty provisions which enforce conditions which aid in monitoring or which makes difficult a test procedure which cannot itself be detected, e.g., X ray temperature measurements. In addition, certain monitoring techniques complement each other, when used together

properly, while others tend to overlap or leave large gaps in their technical coverage when combined. It is therefore advisable to seriously consider which combinations are to be negotiated into a treaty. These subjects are discussed in Section 5.

The techniques discussed here are: (1) seismic, (2) SLIFER, (3) radiochemistry, (4) infrared, (5) gravitational anomaly, (6) acoustical sounding, (7) electromagnetic sounding, and (8) canister leakage measurements. Methods 1 through 3 are established and are generally used for yield determination. Methods 5 through 7 would be used for locating hidden chambers or tunnels, indicating a nuclear effects test or a diagnostic measurement. EMP may also be used for this. Methods 3 and 8 can be used for explosive design identification. Seismic, infrared, and EMP techniques can possibly be used for multiburst detection.

3.2 MINIMAL NUCLEAR EFFECTS TESTING REQUIREMENTS

In these discussions, reference will sometimes be made to the detectability of a 20 meter radius spherical chamber. A nuclear weapons effects experiment is usually performed using a long (~ 200 m) vacuum pipe to attenuate the X ray and neutron radiation through geometrical ($1/r^2$) attenuation (see Figure 2-1). This technique makes efficient use of the radiation, without altering the spectrum, and allows recovery of the target. However, a 200 meter long iron vacuum pipe, with associated tunnels, etc., would be difficult to hide in a PNE. In the second part of this report, we investigate the minimum requirements for a useful effects test and determine that it can be performed in a hydrogen or helium filled chamber of about 20 meters radius. Only a segment of the sphere is needed for the test, but we assume a 20 meter sphere as the model for detectability determination.

3.3 SEISMIC TECHNIQUES

Seismic techniques have been the mainstay of the nuclear burst detection business[1,9] because of the long standoff distances that are required to detect them when the sensor array cannot be located on the territory in which the explosion is occurring. These sensors are generally located in the "teleseismic" zone where they receive signals which have propagated down into the earth's mantle and then back to the surface. This down and up path is dictated by refraction effects, the wave velocity being greater with increasing depth, and by scattering from the earth's core. Surface waves are, of course, also received by these stations. Seismic stations are used to locate the explosion and estimate its yield. Monitoring techniques must be able to distinguish between earthquakes and explosions. One method in current use looks at the ratio of the surface wave amplitude to body wave (down and up) amplitude.

The monitoring problem in a PNE is somewhat different. Seismic techniques would serve two purposes: yield determination and hidden explosion detection. The PNE might be used to mask a second explosion which is used for some illegal purpose. A hidden explosion might be detected in one of two ways. First, it may be separated enough in space or time to allow its shock wave to be discriminated directly or through an analysis of the data collected by a seismic network, i.e., one would expect an identifiable interference pattern to develop. Secondly, if the explosions are close, and the hidden one is not too small, it may be identified as a discrepancy in the yield measurement. The usual problems with local geology must be considered, e.g., interactions of shock waves with strata of differing properties, water content (affects effective cratering yield), movement of ground layers, depth of burial (cratering or contained), etc.

Some of the parameters which can be related to yield are peak particle acceleration, velocity, and displacement. The frequency spectrum of these quantities can also be used to give information about the explosion and its geological environment.

Empirical expressions for peak acceleration, velocity, and displacement have been devised using a regression analysis of underground test data. The quantities are fit to a function of the form

$$A^* = K\, Y^n\, R^{-m} \tag{3-1}$$

where Y is the yield in kilotons and R is the radial distance in kilometers. The data was taken at stations ranging from 0.25 km to 600 km. Table 3-1 shows the values for the constants K, n, and m, for bursts occurring in hard rock and alluvium and for contained and cratering explosions.

One of the methods for seismically concealing an explosion, which may be applicable in the PNE evasion problem, is the use of decoupling.[1,13] The strength of the signal is reduced by firing the explosive in a low coupling medium or in a cavity. Alluvium is an example of a low coupling medium. Large cavities can be solution mined in salt domes or the cavity from one explosion can be used as the decoupling cavity for a later smaller explosion. The decoupling of a 5 KT burst at 800 meters depth, for example, requires a 100 meter diameter spherical cavity.[1]

Table 3-1. Regression equations for peak amplitudes. R is the distance to the burst (kilometers) and Y is the yield (kilotons).

Quantity $A^*=K\,Y^n\,R^{-m}$	Media	Contained Explosion K	Contained Explosion n	Contained Explosion m	Cratering Explosion K	Cratering Explosion n	Cratering Explosion m
Acceleration (a) (Units: g)	Total	.109	.61	1.43			
	Alluvium	.009	.624	1.36	.0321	.497	1.30
	Hard Rock	.157	.656	1.68	.194	.300	1.64
Velocity (v) (Units: cm/sec)	Total	4.92	.646	1.34			
	Alluvium	5.10	.635	1.31	.986	.724	1.15
	Hard Rock	3.36	.77	1.51	.979	.475	1.80
Displacement (d) (Units: cm)	Total	.419	.761	1.18			
	Alluvium	.449	.767	1.14	.0976	.818	1.02
	Hard Rock	.378	.852	1.39	1.53	.600	1.70

3.4 SLIFER MEASUREMENTS

The SLIFER (Shorted Location Indicator by Frequency of Electrical Resonance) technique is commonly used to determine burst yield,[15] and is currently allowed under the draft PNE treaty. The technique measures stress-wave position as a function of time. This dependence is related to yield. The yield measurement is almost completely independent of the type of material in which the burst occurs and requires only accurate measurement of shock front position as a function of time following the detonation. Position, time, and yield are related through Equation 3-2.

$$\frac{R}{Y^{1/3}} = a\left(\frac{t}{Y^{1/3}}\right)^b \qquad (3\text{-}2)$$

where R is the radius from the burst (meters), Y is the yield (kilotons), and t is the time (milliseconds). The constants a and b have been empirically determined to be approximately 6 and 0.47 respectively.

The SLIFER system utilizes the fact that a shorted coaxial cable less than a quarter wavelength long acts as an inductor. The cable is laid radially away from the burst, within the hydrodynamic shock region. It forms a part of the tank circuit of an oscillator, whose frequency will then change as a function of time as the shock wave passes along the cable, crushing it, and shorting the outer conductor to the center wire. The measured parameter is frequency vs. time. From the frequency, the length of cable can be determined and this gives shock position as a function of time.

3.5 RADIOCHEMISTRY TECHNIQUES

The principal value of radiochemistry is the ability to tell, from post-test sampling of radioactive slag by drilling cores, the type and amount of fissionable material in the nuclear device. This could serve as a limited check on the nuclear device to see if it is "as advertised" or whether some device development is being done under the guise of a PNE. Probably, more than any of the other monitoring methods discussed, radiochemistry, tells the least about whether weapons effects testing is being done.

Measurement of the isotope concentrations in radioactive slag near zero point can give the fission yield. The highest concentration of fission isotopes is at a point under the explosion point. This slag point is located a distance D under the explosion point where D is given by Equation 3-3

$$D = 70 \frac{Y^{1/3}}{(ph)^{1/4}} \qquad (3\text{-}3)$$

where

Y is yield in kilotons,
p is average overburden density (2 g cm^{-3}),
h is depth of explosion burial, meters,
D is distance from explosion point where maximum concentration of isotopes exists, meters.

After obtaining a sample of the radioactive slag, usually by coring, the concentrations of residual fissionable material and various radioactive isotopes are measured. Tabulated values of the theoretical fission mole fractions of these isotopes must also be identified. The fission yield

is given by Equation 3-4

$$Y^f = \frac{7 \times 10^{-24} N_o}{1 + \frac{p \Sigma_i \alpha_i}{\Sigma_i N_i}} \tag{3-4}$$

where

Y^f is the fission yield in kilotons,

N_o is the total number of atoms of fissile material in the nuclear device,

p is the measured number of atoms of residual fissible material in the slag sample,

α_i is the tabulated mole fraction of the ith isotope per atom of fissioned material

N_i is the measured number of atoms of the ith type of isotope in the slag sample.

The summation is taken over as many species, i, as feasible to enhance the accuracy. N_o can be stated in terms of Y from knowledge of the energy efficiency for most fission devices (kilotons of yield per kg of fissile material). Also, isotope species with radioactive half lives long compared to the coring, sampling, and measuring times must be used. Those with atomic mass numbers around 95 and also around 140 have the highest mole fractions (α's). Some examples of these are, (with half life given in parenthesis), Cs^{137} (33 yr), Sr^{90} (28 yr), Ce^{144} (290 days), Zr^{95} (63 days), Y^{91} (53 days), Sr^{89} (54 days), Ce^{141} (32 days), Pr^{143} (14 days), and Ba^{140} (13 days).

The accuracy is improved if a large number of spatially different slag samples are used to measure the p and N_i values.

In the beginning of this study, the possibility of gaining increased accuracy through early sample recovery and processing was considered. One could envision a portable laboratory starting to analyze very short lifetime species in the field and while the sample was on the way to the laboratory. Indications from experts in the field are that such early analysis would not be particularly helpful. The possibility should not be considered closed however. The same is true of the possibility of hindering a weapons test by enforcing a treaty provision which would prevent radiochemical samples from being taken for a significant period after the explosion.

3.6 INFRARED TECHNIQUES

Infrared techniques are now being developed for possible application in CTBT monitoring. The objective is to develop a method for confirming that an explosion has taken place. These techniques do not seek out the heat from the burst; it would take many years for the heat from an UGT to diffuse to the surface. Rather, the site of the explosion would be indicated by disruptions in the character of the infrared emissivity and reflectivity of the surface. These disruptions are caused by the shock wave as it strikes the surface from below and shakes up dirt and dust.

Infrared techniques are not yet well developed. The major problems lie in the area of data processing. At the present time, a before and after picture is required so that differences can be determined by computer processing of the data. Even then, it is difficult to identify the explosion site because of natural noise.

Even if these methods were well developed, it is not clear that they would have application in PNE monitoring, since one is not usually interested in finding an isolated explosion site. It would be much more difficult to determine whether there was two explosions instead of one, for example.

3.7 GRAVITATIONAL ANOMALY DETECTION

Since a cavity of 20 meter radius represents a substantial mass of material, it is possible that moving a gravity meter on the surface near a buried nuclear device might reveal the presence of such a cavity. The problem is to determine what effect such a cavity might have on the acceleration of gravity as measured from the surface, i.e., whether or not the presence of the cavity might be detected by noting the decrease in "g" measured by a gravity meter on the surface. Presumably the depth of the cavity would be at least 200-300 m, depending on the device energy yield, since this is the optimum depth for earth moving. The maximum order of magnitude change in "g" can be found by taking the cavity to be spherical and of a radius of 20 meters. Denoting the mass of earth removed for the cavity as M_c the cavity radius as r_c, depth d, M_e and r_e the mass and radius of the earth respectively, the fractional change in g on the earth's surface produced by the cavity is

$$\frac{\Delta g}{g} = \frac{M_c}{d^2} \Big/ \frac{M_e}{r_e^2} = 1/4 \left(\frac{r_c}{d}\right)^2 \frac{r_c}{r_e} \tag{3-5}$$

where the 1/4 is roughly the ratio of soil and rock density to the mean density of the earth. Taking $\frac{r_c}{d}$ as 10^{-1} and $\frac{r_c}{r_e}$ as roughly 4×10^{-6}, $\Delta g/g$ comes out to about 10^{-8}.

Dr. Pierre Goupillaud, a mining exploration geologist, states that 10^{-8} is near the limit of precision for present day gravity meters. Furthermore, small changes in the earth density near the surface, due to various geologic formations, can produce the same change in g as a larger change in density at larger depth, such as the cavity. Note that a 10^{-8} change in the gravity field can also be obtained by a change of 35 cm in the altitude of the gravity meter! In summary, working near the limit of

precision of the apparatus combined with the effects of uncertain geology very near the surface, make the gravity meter very risky for detecting an underground cavity which might surround a PNE device. Gravity measurements would, therefore, only be of value when used with data from other detection methods.

3.8 ACOUSTIC SOUNDING TECHNIQUES

Acoustic sounding is a highly developed science and art used principally for mineral exploration. The general principle consists of the measurement of an echo, due to an active signal source on the earth's surface, from regions where there are abrupt changes in the acoustic impedance of the earth. Detection of a 20 meter cavity surrounding a nuclear explosive buried at the optimum depth for cratering, 200-300 meters, is a possibility; but past experience in the detection of underground tunnels has shown that the method is marginal. This is largely due to the background noise from echoes which emanate from various types of heterogeneities in the local soil and rock geology. Admittedly these discontinuities are not as drastic as a cavity, but they may be closer to the receiver so that their effect on signal to noise is substantial. However, theoretically the signal to noise ratio could be improved by a network of signal sources and receivers with real time computer analysis of the complicated matrix of data. This is an area where further work would be beneficial.

While it is difficult to detect test cavities from the surface, it would be possible to do so by lowering an acoustical system down the emplacement hole just prior to the insertion of the explosive. Listening devices might then be used to ensure that subsequent tunneling did not occur, such as from a previously dug side drift.

3.9 ELECTROMAGNETIC SOUNDING TECHNIQUES

As with acoustical sounding, electromagnetic sounding is an established science and art. There are a wide variety of electrical techniques which are used in geological work.[16,17] Most of these would not be very useful in the search for hidden cavities and tunnels. If the search is made from the surface, sounding techniques analogous to acoustic techniques would seem to be the most appropriate. A pulsed or continuous wave (or swept frequency) signal is transmitted into the ground where it reflects off of anomalies and interfaces between strata of differing electrical conductivity. Since electrical conductivities differ more widely than sound conducting properties, electromagnetic (EM) methods are often more sensitive to the presence of different materials. However, EM signals are also more seriously attenuated in the conducting material and this limits the depth to which they can be useful. Lower frequencies have longer skin depths and hence penetrate farther. The skin depth, or e-fold attenuation distance, is given by

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \tag{3-6}$$

where σ is the material conductivity (mhos/m), ω is the signal frequency (radians/second), and μ is the magnetic permeability ($\mu_0 = 4\pi \times 10^{-7}$ henry/meter = permeability of free space). Since it is the longest wavelengths which penetrate the farthest, the possible resolution decreases quickly with increasing depth.

A formula can easily be derived to illustrate the difficulties in using EM sounding techniques to detect a chamber or object deep underground. As an upper limit, consider the magnetic field scattered by a perfectly conducting sphere. The incident field is a plane wave propagating down from the surface of the ground. The magnetic field (theta component)

scattered by a sphere of radius b, in a medium of conductivity σ, can be found to be

$$H_s = -\frac{1}{2} H_o \left(\frac{b}{r}\right)^3 \sin\theta \; e^{-\gamma(r-b)} \; [(\gamma r)^2+(\gamma r)+1] \tag{3-7}$$

where $\gamma = (1+i)/\delta$ and H_o is the field incident upon the sphere. H_o is assumed to be uniform about the sphere so that the expression is only valid for wavelengths long compared to the sphere radius. Assume that the sphere is at a depth z and that the incident field has a value $H_p(\omega)$ at the surface. Then

$$H_o(\omega) = H_p(\omega) \; e^{-\gamma z} \tag{3-8}$$

and, with $r = z >> b$, $\sin\theta = 1$, the ratio of the field scattered back to the surface to the value originating there is

$$\frac{H_s(\omega)}{H_p(\omega)} = -\frac{1}{2}\left(\frac{b}{z}\right)^3 e^{-2\gamma z} \; [(\gamma z)^2+(\gamma z)+1] \tag{3-8}$$

This is an overestimate because: (1) the sphere is perfectly conducting, and (2) the incident field is a plane wave.

Figure 3-1 is a plot of the magnitude of this ratio as a function of frequency for a 20 meter radius sphere in a ground with conductivity $\sigma = 10^{-3}$ mho/m. Curves are shown for various depths, z, ranging from 100 meters to 1000 meters. From this plot, one can see the rapid return signal loss with both depth and frequency. The lowest frequencies, which give the largest scattered field magnitude, provide the least resolution, i.e., the least ability to provide identification or location of the scatter and are therefore more susceptible to interference from other scatterers.

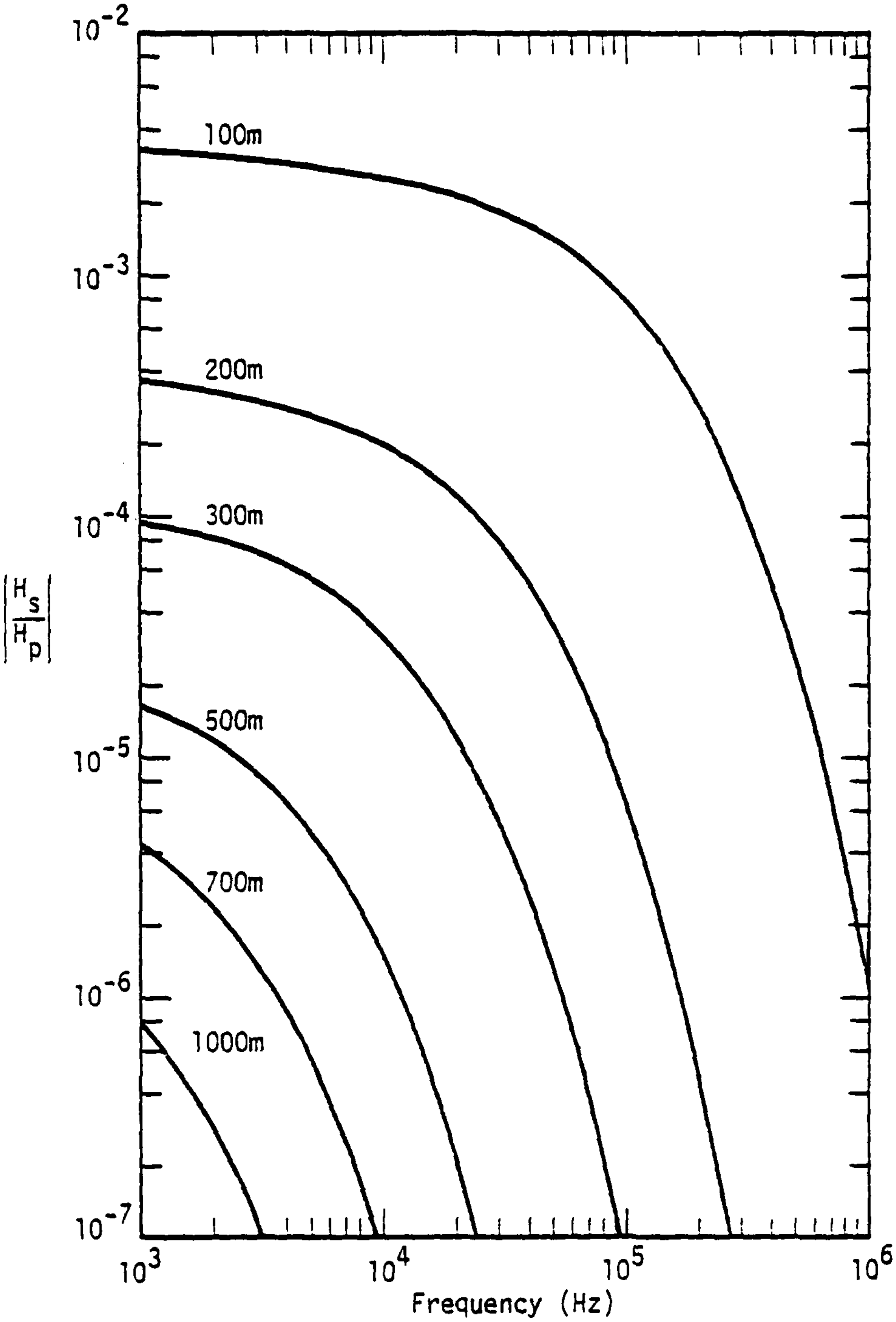

Figure 3-1. Magnitude of the ratio of the magnetic field scattered by a sphere of 20 meters radius to the incident plane wave field at the earth's surface. The ratio is given as a function of frequency for several sphere depths. Ground conductivity is 10^{-3} mho/m.

It may be possible to use a sensor network concept to aid in eliminating noise due to scattering from strata and other scatterers which have "signatures" different from a cavity. It may also be possible to make use of scattering resonances. Equation 3-8 is not valid near resonance. The lowest resonance of a cavity will occur at wavelengths (skin depths) near the circumference of the cavity. For a 20 meter cavity, this occurs at a frequency of about 20 kHz in a ground of 10^{-3} mho/m conductivity. The resonance would be about 2 MHz for a sphere in free space.

The search for a chamber or tunnel near the known PNE explosive can be made from a borehole, rather than the surface, since to be useful, it must have a line-of-sight to the explosive. Such a search might be made by lowering a transmitter/receiver down to the working point or perhaps lowering a dipole antenna and monitoring changes in the antenna input impedance, which varies with the ground characteristics. Again, one may make use of cavity resonances to help identify the cavity as the scatterer.

3.10 CANISTER EMISSIONS MONITORING

One method which can be used to detect whether design changes are being made in the explosives used in a PNE, signaling a possible weapons development program, is to monitor the various emissions from the weapon canister.

The nuclear radiation carries information about the fissile materials as well as the location and size of the core. Thermal radiation may provide location and size information. Both techniques can be countered by providing canisters with thick walls or liners of high Z_1 materials. However, this limits the ability of the party conducting the explosion to obtain diagnostic information (see Appendix).

The technologies required to perform the radiation monitoring task already exist. In the case of nuclear radiation monitoring, the technologies can be adapted from those developed under three programs: NEST (Nuclear Emergency Search Team), MRV verification, and a Navy program for monitoring radiological hazards to personnel living in close proximity to nuclear weapons for prolonged periods.

Under the NEST program, techniques are being developed to find and analyze the construction of terrorist nuclear weapons. Since that, in some ways, is a more difficult problem (requiring equipment which can search out the device from a distance and behind obstacles and requiring highly portable equipment which can be brought in for detailed analysis), it is quite likely that the techniques can be transferred intact to the PNE problem.

It should be noted that Rad-Safe operators are an integral part of the existing DoE/NVOO PNE on-site yield verification process as presently allowed by treaty and that emissions monitoring could be considered an extension of this safety measure.

3.11 RADAR REFLECTIVITY MEASUREMENTS

The infrared technique, discussed previously, operated on the principle that the area of the explosion would have different emission and reflection properties than normal after being disturbed by the shock wave from an underground explosion. Another technique involving similar principles of reflectivity variations utilizes microwaves instead of infrared radiation. This technique may hold even more promise as a method for detecting explosions because the source of the radiation (radar transmitter) is controlled and there is negligible noise from natural sources. However, as with the infrared method, there are massive data handling problems, especially when

large areas must be scanned. The data storage and processing problems are probably the limiting factors utilizing radar reflection.

As with infrared, it is difficult to see how the radar technique could be applied in a PNE situation, unless it proves possible to detect multiple explosions through the patterns produced by the interfering shock waves on the surface.

SECTION 4
ELECTROMAGNETIC PULSE MONITORING TECHNIQUES

4.1 INTRODUCTION

In this section, we consider the possibilities for using the electromagnetic pulse (EMP) emitted by an underground nuclear burst for the purpose of monitoring PNE's. The concept of using EMP to detect underground tests is not new. A discussion of this point is included as Section 4.2. A large part of the effort pursued under this contract was the collection and evaluation of EMP data taken on underground tests. We were particularly fortunate to obtain the cooperation of John Malik and others at Los Alamos Scientific Laboratories (LASL). They have supplied us with a large amount of data and it has taken much of our time to absorb, sort, and analyze just a part of it. We feel that the effort was quite rewarding even though it is incomplete. While underground test EMP is still a mysterious phenomenon, it is not quite as mysterious as it used to be. We think we are in a much better position to perform meaningful and fruitful experiments. Most importantly, it appears to be a potentially useful monitoring and detection tool when the proper measurements are made.

Section 4.3 discusses the range of theoretically possible sources of EMP. Section 4.4 is a summary of the results of our data analysis; a more detailed account is given in a separate report. Section 4.5 is a discussion of possible ways to monitor a PNE using EMP. Finally, Section 4.6 includes suggestions for future experiments.

The various purposes for which EMP can potentially be used in a PNE monitoring system are

1. Multiple (hidden) burst detection and location
2. Yield estimates
3. Event timing in signal
4. Radiation time history
5. Detection of hidden tunnels or chambers

The first of these, multiple burst detection, appears to be the most practical and easily implemented utilization, so long as no diagnostic information is being sought. It has been established through experimental measurement that detectable EMP signals can be emitted by an underground burst. However, the phenomenon is not easily predictable. Signals have been detected by surface sensors at distances on the order of ten kilometers from bursts of a few kilotons and it is reasonable to expect that sensors placed close enough to an explosion could detect its presence and separate signals from different explosions which occur within a period measured in milliseconds or greater. This point will be discussed in Section 4.5. Even though the proven range of EMP detectability is quite limited*, thus allowing a widely separated burst to go undetected by this means, the EMP system may force a clandestine shot to be placed at such a distance as to be separately detected by a seismic or acoustic array or by an electromagnetic array sensitive to the passage of the shock waves from the two explosions. In other words, EMP and shock wave monitoring systems can be used to complement each other, with the EMP system monitoring bursts closely spaced in time and space and the shock wave system monitoring bursts more widely separated in time and space. This subject is discussed in more detail in Section 4.5.

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* The recent data analysis indicates that EMP may be monitorable at larger distances if a wider bandwidth system had been used. This possibility should be pursued.

Item 2 of the EMP utilization list is "yield estimate". Correlations between yield and EMP signal strength have been attempted in the past[20] but are far from reliable. This is consistent with the fact that the source mechanisms are numerous and not easily predicted. At some time in the future, it may be possible to isolate a specific part of the EMP waveform and use that part to make a yield estimate.

Attempts have been made in the past to obtain gamma and neutron radiation time histories from the EMP signal recorded at the surface. Fast signals do propagate to the surface, but the feeling is that the propagation must be along the cable bundle and experience indicates that this fast signal is so dependent upon the bundle/trailer park configuration that the extraction of such time histories is unreliable if not practically impossible. It may be possible to bury sensors close enough to the burst to obtain a radiation time history. However, such time histories reveal weapon design information which most treaty signatories would not desire to have revealed. Therefore, any monitoring system which threatened to reveal it would most likely not be allowed under a treaty.

In our original proposal for utilizing an EMP monitoring network, the emphasis was on the problem of detecting the existence of hidden chambers or tunnels near the burst which would be used for clandestine nuclear weapons effects tests or nuclear weapons diagnostic measurements (Item 5). In its simplest form, the technique was basically one of looking for asymmetries in an otherwise symmetrical EMP signal, e.g., an azimuthal symmetry about the borehold to the surface. By looking for asymmetries, rather than relying upon an anlysis of the form of the signal received by a single sensor, one eliminates the need to entirely understand or predict the

nature of the signal. We no longer consider this to be practical* although it may become so at a future time when EMP is better understood.

* One of the more practical methods for insuring the absence of cavities near the burst point would consist of the following procedures. First, a treaty provision is included which allows observers to be placed on the PNE site between the time that the borehole is finally drilled and the time that the explosive is emplaced and stemmed. Before emplacement, an electromagnetic or acoustical sounding device is lowered into the borehold to inspect for the presence of a cavity or tunnel (or a metallic pipe). After the inspection, the explosive is emplaced and the hole stemmed. Listening devices and visual inspection can then be used to prevent additional excavation, such as might be attempted from a side drift. One may still wish to use EMP techniques as a final assurance, but this will probably require several boreholes to place sensors close to the bursts in a specified pattern.

4.2 COMMENTS ON PREVIOUS EXPERIMENTAL EFFORTS

EMP measurements have been made by LASL, LLL, Sandia Corp., EG&G, and the U.S. Geological Survey*. With the exception of the data taken by Zablocki (USGS), none of the measurements have been published openly. Moreover, there has been no great effort to exchange data or to publish it in any form. Wouters (LLL) has the most extensive collection. Malik has recently collected and distributed much of the recent data taken by LASL, in the first effort to involve members of the EMP community. SANDIA Corporation has published more data than any other organization, albeit in classified form.

EMP measurements have been made for three reasons: (1) to determine if EMP signals could be used for test detection/diagnostics; (2) to determine the nature of the noise induced on signal carrying cables; (3) to study the phenomenology of UGT EMP. Most measurements have not been controlled experiments designed to investigate the phenomenology; they have not used the best equipment and they have not taken the large amount of data that would be required to define the spatial distribution of the fields including correlations of fields near the burst with fields at the surface. A good picture of the spatial distribution as a function of time is important because the complex signals emitted by an underground test appear to be a composite of signals generated by different source mechanisms. These individual components are not present in the same proportion on any given shot. Many factors are involved, including, apparently, geological factors. Signals have been measured in different time ranges on different shots. It is known that the signals have structure in the microsecond region on

* The French have also made measurements during their tests under the Sahara.

through the second time frame, the latter undoubtedly due to shock wave phenomena. In fact, one can take a piece of data taken on the microsecond time frame, cover up the time scale, and it would be difficult to distinguish it from a piece of data taken in the millisecond region or the hundred millisecond region.

A large amount of data has been taken over the last twenty years or so, but much of it is of little value because of the lack of planning and the quality of instrumentation. It was often taken with a "lets see if anything is there philosophy" and there has been very little theoretical analysis of the data that has been taken. The anlyses that have been made were performed by Wouters (Lawrence Livermore Laboratory), Malik (Los Alamos Scientific Laboratory), Vittitoe (SANDIA Corporation), U.S. Geological Service, and, most recently, by Messier (Mission Research Corporation).

Much of the data is of limited usefulness because it was taken with instrumentation of too low a frequency response. Experimenters apparently assumed that the signal measured at the surface had diffused upward from the source and therefore it had lost its high frequency components. The assumption that the magnetic bubble was the prime generation mechanism seems to have dictated the design of most experiments rather than a more unbiased attitude. In any case, the high frequency spike produced by the UGT was sometimes responsible for exciting the low frequency equipment to the extent that the measured signal is largely the impulse response of the instrumentation rather than a measure of the true signal.

Measurements made by LASL since 1970 do not have this problem, but are somewhat limited by a 20 kHz recorder bandwidth (with some exceptions). LASL has gathered a large quantity of data which Messier has begun to analyze under the provisions of this contract. SANDIA Corp has made several high frequency measurements (megahertz bandwidth) in order to

determine the feasibility of using EMP to obtain certain types of diagnostic information. With one exception, measurements were made only to a few microseconds (the exception was a 500 microsecond measurement). These were high quality measurements and the negative conclusions based on them were justified to the extent that they were intended to apply.

Specifically, it was determined that, while there was high frequency information available in the signals, it would be nearly impossible to extract the diagnostic data from the signal. This is because the high frequency signal is highly dependent upon the cable/instrumentation trailer configuration. It is the cable bundle which carries the high frequency signals to the surface. The shield currents vary from cable to cable and ringing occurs because of the various impedance mismatches which the currents see along their path.

We do not feel that this conclusion should prevent the future study of EMP as a detection/diagnostic tool where lower frequencies than a megahertz would be useful, or where other approaches to the problem might be possible. The LASL data, which covers a wide range of times shows, in conjunction with other data, that the EMP signal has a highly complex structure. This complexity makes analysis difficult, but it also increases the possibility that a wide variety of information could be gained from the data, especially if it was analyzed in conjunction with other types of data, such as seismic data.

High frequency measurements have only been made close-in. All distant measurements (sev eral kilometers or greater) have been low frequency. They have also been confined to the surface of the gorund. If there was a high frequency signal there, it would not have been measured because of the instrumentation response. If high frequency measurements had been made, it is quite possible that they would have missed the radiated signal if it is radiated upward rather than horizontally.

4.3 SOURCES OF EMP

There are many possible sources of measurable electromagnetic fields produced during an underground explsoion. To aid in describing these mechanisms, we provide Figure 4-1, which shows a composite PNE or weapons test and nuclear effects test. There seems to be very little difference in the configurations used in a PNE or a typical weapons test. In both cases, a vertical hole is drilled in the earth to the desired depth. Steel casings may support the sides of the drill hole or a pipe string extends down to the explosive. The explosive and diagnostics canisters are placed at the bottom of the hole, with cables leading from the explosive and diagnostics canister to the surface through the borehole. To prevent venting, the hole is tamped, i.e., filled with earth-like material. The basic difference between a typical weapons test and PNE as viewed from the surface could lie in the number of signal cables that are required and in the diameter of the drill hole. It would be advantageous to be able to use standard size drills in PNE work, which would imply smaller sized holes than are sometimes required by weapons tests because of the number of signal cables used and the size of the canister. A fully developed peaceful nuclear explosive should require a relatively small number of cables because extensive diagnostics are not necessary.

A nuclear weapon effects test ordinarily involves the use of a vacuum pipe on the order of 200 meters in length. The pipe is placed in a drift which is longer than the pipe. The drift is "stemmed", i.e., filled with grout, from the zero room out to a sufficient distance along the pipe ($\sim$100 m) to aid in containing the explosion. The purpose of the vacuum pipe is to transport the X-ray flux a sufficient distance to the experiment, using geometrical attenuation to reduce it, without significantly distorting the spectrum. Distances can be reduced by using hydrogen or helium to attenuate the flux and, perhaps, remove the need for a metal pipe, depending on what pressures are used. Coaxial cables go from

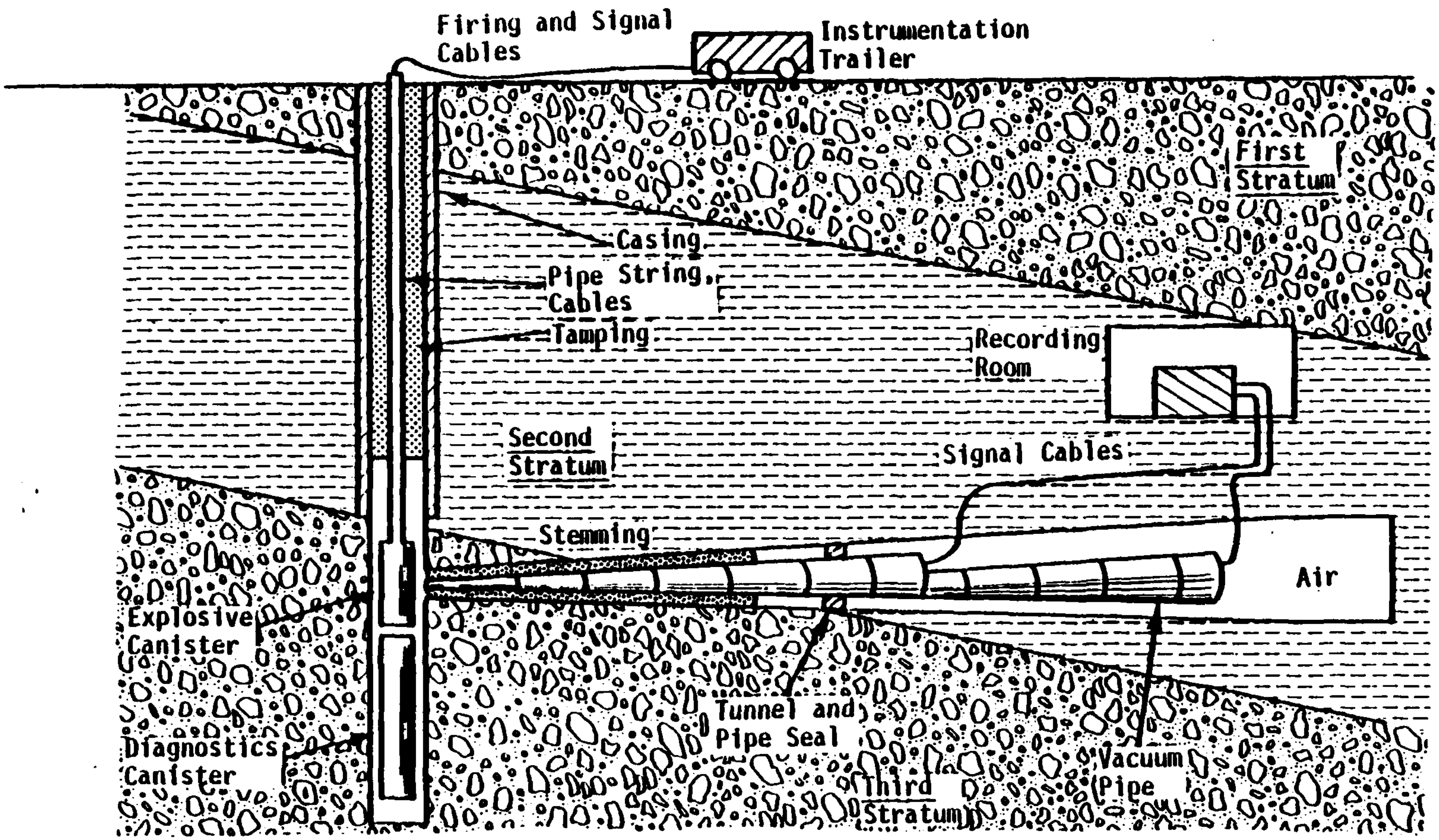

Figure 4-1. Schematic diagram of a combined weapon test (or PNE) and nuclear effects test for the purpose of illustrating technical terms.

the exposure area to recorders which are at distances great enough to allow the equipment to survive the shock wave. Metal rails may remain in the tunnel from the construction operation.

Table 4-1 lists various possible sources of underground burst EMP in terms of the phenomenology associated with it. The phenomenology determines the characteristic times associated with the signal.

The first category of EMP is that resulting directly from Compton electron currents generated by prompt gamma radiation (and gammas resulting from neutron collisions). In this category, the most obvious source is probably the electrical dipole caused by asymmetries in the explosive, its canister, its position within the chamber, and the chamber itself (with accompanying instrumentation, explosive supports, rock bolts, etc). The steel casing can act as a waveguide, bringing energy up to the surface to be radiated at the top. It is a very lossy waveguide because of the tamping material that fills it. Compton currents entering a chamber or tunnel filled with a gas, e.g., air or hydrogen, will produce an extended source of EMP. This will also be the case with photons exciting a vacuum pipe continuing down the tunnel in which the pipe is located. The tunnel can act as a waveguide for EMP produced within it.

The second category of EMP sources involves the existence of replacement currents on conductors such as cable shields, rails, and the other surface of a pipe string, metallic casing, or vacuum pipe. The term "replacement current" is used in a very general manner. It refers to the currents induced upon a conductor due to the emission of photoelectric and Compton currents from some part of it or from an object to which it is attached. It is thought that electromagnetic radiation from cables or the outer surface of the casing leading to the ground surface is one of the important contributors to the EMP signal seen by surface observers.[23,24] The same filtering process which removes high frequency components from

Table 4-1. Underground burst electromagnetic signals classified phenomenologically.

I. Prompt Radiation Currents

1. Explosive/cavity asymmetry (multipole).
2. Local fields in radiation zone.
3. Guided wave within casing, emission from top.
4. Compton currents in gas filled tunnel.
5. Tunnel waveguide.

II. Replacement Currents

1. Outer casing (vertical hole).
2. Cables, rails.
3. Vacuum pipe (external).

III. Plasma Motion

1. Magnetic bubble (expanding cavity and tunnels).
2. Plasma seepage into faults and fissures.

IV. Shock Wave and Pressure Phenomena

1. Electroseismic effects.
2. Geomagnetic field "pushing".

V. Propagation Effects

1. Underground diffusion effects.
2. Reflections from ground strata and the surface.
3. Surface propagation effects.

fields propagating through the ground acts upon the currents propagating along a cable so that the pulse is attenuated and dispersed as it propagates up to the surface. The length of the line determines the low frequency response. Only the lowest frequency components survive to be reflected from the end of the line. The buried line should not ring significantly, because of damping by the conducting material, although the existence of dielectric covers on the cables and differential propagation modes between cables in a bundle will aid in the propagation of currents along the line.[25] Currents that reach the surface and propagate on lengths of cable lying there can radiate, and ring due to reflections at the instrumentation trailers and the air/ground interface.

The third category of EMP generator includes those phenomena associated with the motion of geomagnetic field lines tied to moving hot plasmas. The most familiar of these phenomena is the "magnetic bubble" formed at the point of the explosion. This is also considered to be a major contributor to the total EMP signal. Here, the fireball, composed of ionized ground materials, expands and pushes out the geomagnetic field, which cannot penetrate the highly conducting plasma. In the simplest case, that of a spherical fireball, the resulting disturbed field is described by the vector sum of the original geomagnetic field and that due to a magnetic dipole placed at the center of the sphere. The magnetic dipole moment is proportional to the volume of the fireball. An approximation to the fireball radius is[20]

$$R = 17\ Y^{1/3} \quad , \tag{4-1}$$

where R is the radius in meters and Y is the hydrodynamic yield in kilotons. If the explosion is in a large cavity, such as might be used for decoupling purposes, the cavity radius would most likely determine the

explosion volume, since these radii are typically larger than those indicated by Equation 4-1. One example that has been used for decoupling cavities in salt[7] is equivalent to

$$R = 25\ Y^{1/3} \tag{4-2}$$

The ratio of the no-cavity fireball volume to decoupling cavity volume is then approximately three (ignoring any increased effective volume due to cavity wall ionization, which should not be significant). This factor is also the increase in dipole field strength.

Geomagnetic field variations can also be caused by plasma motion into tunnels and cavities near the burst and by plasma seepage into faults and crevices in the earth. The field variations from this phenomena could be significant. They are also difficult to predict in a given situation.

The fourth category of EMP generation mechanisms is associated with mechanical stresses and their coversion to electrical signals. Such transient signals are observed in chemical explosions, and we now feel that they may play an important part in the generation of portions of the EMP signal. For example, there is invariably a signal radiated when the shock wave reaches the surface and when the shock wave reaches ground potential sensors. These signals may, or may not, be due to the motion of cables, but there are other signals which occur between zero time and the time in which the shock wave reaches the surface which seem to be related more to the presence of a water table. Others seem to be due to acoustical oscillations in the earth. One of the proposed mechanisms is electrofiltration whereby a potential difference is caused by ionic solutions being forced through fissures or across the boundary between chemically dissimilar materials.[18,19,28] This phenomena is known to exist in the case of chemical explosions in the ground[29,30] and it has been shown that electrode effects can be eliminated as a source.[31]

Electrofiltration is also suspected as a source of electric field potentials lasting for many days or months after a nuclear explosion.[19] In this case, the fluid flow is suspected to be caused by steam pressure from heat being trapped in the nuclear cavity. The potential measured at the surface rises for several days and reverses. The reversal in sign would be explained by the water flow reversing direction and flowing back into the cavity after it cools. Ground potentials have also been measured in the vicinity of hot springs, lending credibility to the idea.

We feel that this late time electrofiltration idea should be developed as a method for verifying test ban treaty violations. Suspected sites could be checked for anomalous potential distributions for a period of weeks after the suspected violation. An experimental program would be required in order to develop the technique into a reliable one.

Two sources of noise are important in complicating the measurement of a weak EMP signal: spherics and 60 Hz power line noise. The 60 Hz signal is due to distant power lines and local power equipment. Spherics are the noises generated by lightning from large distances and propagated in the earth-ionosphere waveguide. The high frequency components can survive several trips around the world.

Table 4-2 lists the dominant EMP sources associated with a typical weapons test or PNE. Most are also associated with an effects test. Table 4-3 lists additional sources which are present in a nuclear weapons effects test due to the different geometry associated with it.

Table 4-2. EM signals associated with a weapons test (vertical hole) and PNE.

1. Explosive/canister asymmetry.
2. Local radiation zone fields.
3. Cable/casing transmission line to surface.
4. Cable/outer casing replacement currents.
5. Magnetic bubble and plasma seepage.
6. Shockwave and electrofiltration effects.

Table 4-3. Additional signals due to nuclear effects tests.

1. Compton currents in tunnel (including leakage around vacuum pipe).
2. Compton currents exiting pipe.
3. Pipe replacement currents.
4. Cable, rail replacement currents.
5. Tunnel waveguide.
6. Magnetic bubble (exploding tunnel).

4.4 EMP DATA ANALYSIS

During the course of this PNE monitoring effort, we were given the opportunity to attempt an analysis of much of the underground test (UGT) EMP data taken by Los Alamos Scientific Laboratories (LASL). The data consists primarily of cable current measurements and ground potential measurements over a wide frequency band (up to 20 kHz in most cases). Due to the large amount of data, it was not possible to perform as extensive an analysis as would be possible if more time were available. However, by limiting the types of measurements to be analyzed and the time frame of the data which is analyzed, we were able to produce an evaluation which is relevant to the PNE monitoring problem and, less directly, to the problem of monitoring UGT EMP at larger distances.

It must be emphasized that the data was taken in uncontrolled exmperiments (uncontrolled from the EMP viewpoint); there are many conditions which are far from ideal, such as the geophysical conditions. This, in addition to the fact that the measurement systems and locations were far from ideal means that the data has only limited usefulness in increasing our understanding of the EMP source mechanisms or in aiding us in our understanding of how the EMP signal would vary under the wide variety of conditions to be expected over the spectrum of PNE applications.

The actual analysis, with a selection of data is presented as an appendix. Here, we will describe the general character of the EMP signal and its possible application to PNE monitoring.

When this study began, we did not even know whether EMP from a UGT was an expectable phenomenon in all cases. We now feel fairly safe in the assumption that a "zero time" signal will always be detected if one is within a kilometer or two of the burst. In addition, it seems to be almost

certain that an electrical signal will be generated when the shock wave reaches the surface and when it reaches an electric field sensor such as the ground potential plates commonly used. We do not know if corresponding magnetic fields are generated to a significant extent. The "zero time" signal is of primary importance since it has the highest probability of carrying information about the burst. We will be a little more lenient in the use of the term "zero time" signal than many experiments might be. Any signal seen within the time that a pulse could have diffused from burst to observer, beginning at the time of the explosion, will be considered "zero time". This includes both the very fast pulses which are sometimes seen propagating up cables and the wider pulses which are also seen and which may have diffused along the conductor or through the ground.

The question of the role played by the cables and well casing is an important one. If no signal would be generated without the presence of a cable, then it would be possible to hide a second shot electromagnetically by using fiber optics for the triggering signal and data collection. The data indicates that EMP generated by an UGT is, in general, a complex mixture of signals from several sources. There is often a fast rising and oscillating signal which is propagated up the cable bundle, possibly in a differential mode which reduces the absorption of the signal by the conducting material around the bundle. This signal dominates the lower yield/less deeply buried shots. When measured at a distance, the radiation has characteristics which identify it as radiation from the horizontal cable run extending from ground zero (GZ) to the trailer park. A vertical component has also been measured. These fast signals have been measured with microsecond time resolution and are probably generated by prompt radiation from the burst.

There is a second "zero time" signal which peaks at a time on the order of a millisecond. This seems to be present on all shots, although it may be obscured by ringing from the prompt signal. This signal is seen in the currents running from ground zero, as are succeeding pulses when present, but there is strong evidence that the cables are acting as antennas and responding to fields rather than acting as the field source. A large number of measurements indicate that this pulse is polarized in the radial direction near GZ but after several hundred meters is azimuthal in orientation. There is a large scattering of data and it is difficult to determine the attenuation with distance law. However, it can be seen that the electric fields fall off quite rapidly with range ; $1/r^5$ is an attenuation which seems to fit many cases, where r is the slant range. The reader is urged to see the plots of data points for himself. There is some indication that the azimuthally oriented fields, which dominate at the larger distances, fall off more slowly with surface range. Some fields measured at a few kilometers are much higher than would be indicated by a $1/r^5$ law and $1/r^3$ might be reasonable. In one particular case, the ground potential measurement was made across a "seep" which is a wet area, and it is not clear that the large potential was due more to the geophysical conditions than to the distance. In this case, the ground conductivity may have been a factor. However, the measurement was also to the magnetic north and there are other indications that ground potential measurements made to the magnetic north are larger.* This is not conclusive, however. Another indication that geomagnetic factors are involved is the relative timing of ground potential measurements made along magnetic north-south and east-west axes. With one exception, the north-south signals start and peak a few tenths of a millisecond faster than the east-west signals no matter what the direction from burst to sensor location. The attenuation and timing variations with dependence on magnetic azimuth, as well as the apparent existence of an azimuthal field are indications that a geomagnetic bubble signal does exist, mixed with other types. There are problems with identifying the

* John Malik (LASL) has noted that a large number of the geological faults run roughly in a north-south direction and may be responsible for guiding fields in that direction.

signal with a diffused magnetic bubble, however. There is very little correlation of the signal timing with any obvious range parameter such as slant range, depth-of-burst, surface range, or depth-of-burst plus surface eange. The range attenuation seems to be too fast to correspond to the magnetic bubble signal computed for a step function source, i.e., under the assumption that the geomagnetic field is pushed out and held by the molten material produced by the burst. If the source were not a step function, but a pulse, the range attenuation of the peak field could be greater. This would correspond to the field being pushed out and quickly diffusing back through the molten materials. The geomagnetic field is not held out because the molten material does not have a high enough electrical conductivity. For example, an impulse source in a homogeneous medium in which displacement currents can be ignored produces peak fields which attenuate as $1/r^5$.

Between the "zero time" signal and the "slap down" signal, which occurs when the shock wave reaches the surface and causes the ground to rise up and to "slap down", there is a period in which oscillations and/or pulses are detected. We will refer to this as the "transition period" between the times when the signals can be considered purely electromagnetic in origin and when they can be considered to be of acoustic or seismic origin. We have not had an opportunity to analyze these signals in detail, but from their character, we feel that they are of electroseismic origin. In the data studied, the depth of the burst relative to the depth of the underground water table seemed to be a factor. Bursts at relatively shallow depths had little or no signal in this time frame. Bursts below the water level did have significant structure. Bursts at nearly the same depth had nearly the same time wave forms. These wave forms will probably be predictable when the source mechanism is better understood or they may be used to learn about conditions in the region near the burst. It is possible that this part of the signal can be used in the detection of hidden chambers being used to perform nuclear effects experiments.

The polarity of the "transition period" signal seems to vary as a function of time, being radial some times and azimuthal at others. There also seems to be a geomagnetic influence, which is quite interesting since, if there is a geomagnetic electroseismic signal, it could be important in the generation of the "zero time" signal also.

The "slap down" signal itself is also quite complicated, depending on azimuth and range. It starts during the "transition period" before the shock actually reaches the surface. The cables running from ground zero to the trailer park seem to be important to the radiation and, perhaps, the generation of this signal. This can be seen in the radiation pattern and was obvious in a comparison of the signals radiated by two nearly identical bursts with their signals measured by the same set of ground potential plates. The biggest difference between the two shots was the location of the trailer park. In one case it was to the north of ground zero and in the other it was to the south. The "slap down" signals had the opposite polarity although the "transition period" signals did not. The transition period signals were nearly identical.

Once the "slap down" time begins there is a sequence of oscillations and pulses which continue until the time that the seismic signal reaches the sensors. A very large signal is then generated which obliterates any other signals. We have not yet analyzed the "seismic arrival" signal or the "seismic transition" signals. We feel that studies of their nature would be useful in increasing our knowledge of the earlier signals which may also be caused by seismoelectric effects.

4.5 POSSIBLE EMP MONITORING TECHNIQUES

The design of an optimum EMP monitoring system will depend in part upon the results of future experimental and theoretical efforts which will better define the EMP sources. However, there are certain basic concepts which can be evaluated qualitatively.

In our discussions with personnel concerned with the terms of a PNE treaty, the problem of detecting a hidden explosion seemed to be important. Since EMP offers potentially one of the best mechanisms for counting explosions with good time resolution, we will concentrate on that problem. In particular, we will concentrate on the situation in which the clandestine burst is hidden in the vicinity of the known burst or bursts. Thus, one could have a single charge hidden in a sequence of row charges or a clandestine charge could be hidden near or below a single announced charge, timed such that it cannot be separated acoustically from the known explosion and with its yield small enough to place the effective yield of the two explosions within the uncertainties of the known explosion and the yield measurement.

The easiest detection system to implement is a current sensor in the uphole cable bundle or a current sensor on the SLIFER cable. The cable bundle signal will most likely be a messy one and it is difficult to say whether the EMP from a second explosion could be discriminated. The SLIFER cable offers the potential for a cleaner signal. SLIFERs are allowed in the present draft PNE treaty as the means for measuring yield (see Section 5). By using an insulated SLIFER cable and grounding the shield/instrumentation box to ground at both ends, one obtains a ground potential sensor. One must insure, of course, that the electromagnetic shielding is sufficient to prevent leakage of the shield currents into the interior of the coax line and inducing noise into the measurement since larger shield currents will develop than would if the cable were entirely insulated.

We must now address the question of what electric fields the SLIFER cable can couple to. The cable runs away from the burst point and must see an electric field oriented in this direction. The known burst probably provides a good signal and there is probably experimental evidence along these lines though we have not seen it. The signal would be generated by either an electric dipole source, caused by bomb asymmetry or by currents running on the cables or on the casing of the downhole shaft. In addition, the shockwave itself probably generates a signal. The hidden burst will have some sort of electric dipole signal and cable signal, unless these are deliberately eliminated by removing the cable and using fiber optics for firing and data transmission and by going to great lengths to provide the symmetry necessary to eliminate the dipole signal. The effort required to eliminate these signals is in itself a great deterrent. One false move, so to speak, subjects the perpetrator to the risk of discovery and whatever political consequences that may ensue.

Assuming for the moment that the electric dipole and cable/casing signals do exist and are being radiated by the clandestine explosion. What degree of detectability can we expect from the SLIFER current system? This is hard to assess without experimental data showing the nature of the signals induced on the SLIFER cable. However, from some magnetic field data taken by SANDIA Corporation, we expect to see some sharp microsecond type pulses corresponding to each gamma pulse of the known burst. The signal will then be relatively quiet until shock arrival, which may be several milliseconds later (we do not know enough about the deployment of SLIFERs to be sure).

If the second burst is hidden very close, it will have to be fired with microsecond accuracy in order to go undetected. Even a relatively small explosion would be easily detected as a spike in the waveform during the quiet period or before the known burst goes off. It is likely that such a spike would be detected even in the shock induced signal.

If the burst is farther away, the signal will be attenuated and spread out. However, under realistic conditions, it will have to be several hundred meters away before it could be lost in the noise. The farther away one moves the hidden burst, however, the more likely it can be detected by an acoustic or electromagnetic sensor array on the surface, even if it is removed to a position directly below the known burst.

In the event that the electric dipole and cable signals are eliminated, what can we expect from the SLIFER sensor? The only two remaining signal generators that we know about are the geomagnetic bubble signal and some form of electroseismic signal. The magnetic bubble signal from a burst hidden below the known burst would not be seen by a SLIFER cable because the cable runs in the radial direction but the bubble signal is azimuthal in orientation. However, the electroseismic signal offers good possibilities for burst detection. While analyzing the currents induced in trailer park ground systems, personnel at LASL noted that a component exists which oscillates with a period which increases linearly as a function of time from the microsecond time region into the shock arrival time. Data from several events fit the same period versus time curve, independently of yield and depth of burst. Subsequent investigations showed the possibility that these signals are due to some type of electroseismic effect, i.e., the oscillations are acoustic but are converted into electrical signals. Independently of their cause, such signals offer the possibility of detecting a hidden burst through the regularity of their increasing period. A perturbation due to a second burst should be noticed as an upset in this regularity. Even without the period discrimination mechanism, it may be possible to detect separate shock waves through the currents they induce on the SLIFER cable. The SLIFER itself cannot detect two shocks since its operating principle requires the cable to be crushed by the shock wave it is measuring.

The SLIFER cable current monitoring system was considered because of its relative simplicity and the likelihood that it could be negotiated into a PNE contract. We also need to consider the application of a surface EMP monitoring network, first of all because it has its own inherent advantages and secondly because of certain problems which may arise with the SLIFER system. For example, the SLIFER system may prove to be of limited usefulness because of noise created by the known burst. It may also prove to be capable of monitoring the gamma/neutron time history of the known burst.* This may appear to be an advantage at first, but it would probably rule out the SLIFER current system as a negotiable item, since it would reveal too much about the weapon design.

A surface array has several advantages. First, it is not difficult to deploy. Unlike a seismic array, it would be confined to an area within a few kilometers from the site of the explosions. Isolated recording stations could be used without the problem of transmitting the information back for analysis.

We have assumed that an array of sensors will be deployed rather than a single one. An array has a higher probability of detecting an illegal burst than a single sensor because (1) certain sensors will be in better positions than others and (2) the pattern of signals may yield clues to the presence of a hidden burst that individual measurements could not. For example, the data from an underground burst can be quite messy, consisting of many peaks and oscillations. While it might be difficult to pick out the peaks from the known burst from the peaks of the hidden shot, one might notice a relative change in their positions as a function of range which would indicate that they were generated at different depths.

The exact design of a sensor network and the choice of sensor types will depend upon the nature of the PNE project. The problem of finding an explosion hidden in a sequence of row charges designed to dig a

* Through the EMP signal.

canal is different from finding a single charge hidden in the explosion of another single charge which is being used to extract natural gas deep in the earth. In all of these cases, however, there is the problem of reducing the interference from the known bursts so that the signal from the hidden one can be more easily seen.

If it proves feasible to rely upon the presence of a geomagnetic signal, the optimum network will probably be one which minimizes the uphole cable signals and, if possible, electroseismic signals generated when the shock wave reaches the surface. It is not yet obvious that we wish to eliminate the latter signal since future experiments and theoretical work may show that "slap-down" signals are a useful tool. For the moment, however, we should design a system which utilizes the simplest signal that would exist without the presence of a cable on the unknown burst.

The ground potential measurement technique used by LASL, Zablocki, and others seem to be successful, so we will consider a network based on that type of system. Magnetic field sensors have yet to prove their worth.

Figure 4-2 shows a possible network composed of ground potential sensors arranged in a manner that would allow the signals from the cables running to the trailer park to be eliminated. This design is for a single known burst; obviously it would be more difficult to implement for a series of row charges unless all cables were required to follow parallel paths to the trailer park.

For the same of discussion, assume that the trailer park lies to the east of ground zero (this is just to set up a coordinate system; it is not a recommendation). Then, the N/S arms of the ground potential sensors which lie to the east and west of the cable run are insensitive to the fields radiated by the cables (ideally) but are sensitive to any azimuthal electric field generated by the burst itself. The E/W directed

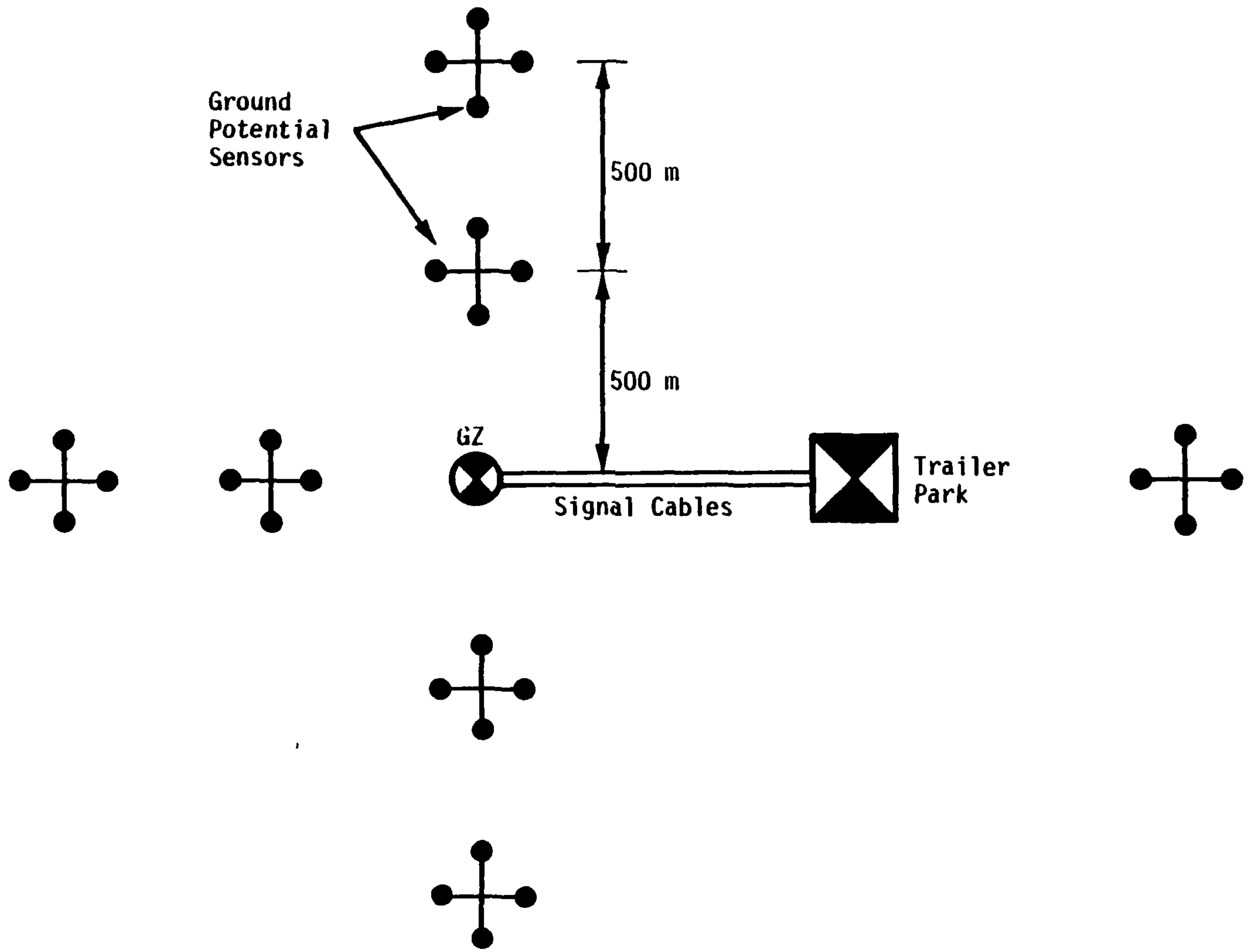

Figure 4-2. EMP monitoring network composed of ground potential sensors and designed to eliminate cable signals from a single burst.

arms of the sensors to the north and south are sensitive to the azimuthal field. Since they are also sensitive to the fields radiated by the cables, the cable signal has to be eliminated by subtracting signals received by stations equally spaced to the north and south. This process reinforces any azimuthally oriented field. The remaining arms of the ground potential stations exist only to make the collection of data more complete. The 500 meter spacing between stations shown in the figure are based on guess-work more than logical analysis. Having stations located within 500 meters of ground zero ensures the acquisition of a strong "signature" for the burst. It should be possible to predict how this would vary with distance from the burst and the theoretical or empirical prediction can be compared with the data received at more distant stations to aid in determining whether an illegal burst was present.

4.6 SUGGESTED FUTURE EXPERIMENTS

The most immediate future experiments should be oriented toward understanding and separating the various EMP sources. Toward this end, we feel that both magnetic and electric field sensors should be utilized. Measurements should be wide-band, with some going up to the megahertz region, but with all covering the 20 kHz band which LASL has already covered. The large bandpass requirement limits the usefulness of the sensitive SQUID magnetic field sensors. We feel that the magnetic bubble signal has not been seen at large distances because the bandpass has been too small.

There should be a large concentration of sensors within 0.5 to three kilometers of ground zero. This appears to be the region in which the electric field polarization changes from primarily radial to primarily azimuthal and is the region in which we will most likely be able to identify the geomagnetic signal; this is the signal which has the potential for serving as a means for remote detection of underground tests.

The ground potential measurements made in the past often had the probes aligned along magnetic north-south and east-west directions. This has shown us some interesting timing differences between the two signals which may be due to geomagnetic effects. In the future, however, we feel that orientations along the radial and azimuthal directions, relative to ground zero, would be more useful in allowing the separation of signals from different sources. An additional probe in the downward direction would also be useful.

It is important to provide geophysical data such as conductivity profiles and water table levels in order to aid the data analysis. Information about the direction of cable runs, trailer park location, and trailer grounds is also important.

In addition to electromagnetic field measurements, there should be measurements of bulk and individual cable currents designed to aid in the separation of cable current sources from other field sources.

Beyond 3 kilometers there should be a lesser density of sensors. Both magnetic field and ground probe measurements would be useful. In any case, the sensors should have at least a 1 kHz bandpass.

Good use can be made of non-nuclear experiments. This type of experiment can help us to separate out the various possible source mechanisms. For example, one can directly pulse cables in a borehole and study pulsed cable radiation directly. Many such holes exist at NTS already. Chemical explosive experiments would help illuminate the role of electroseismic effects, as would laboratory measurements of the physical constants which relate seismic activity to electrical activity.

The late-time electrofiltration phenomenon described in Section 4.3 holds promise of being developed into a technique for verifying treaty violations through on-site inspection many days or weeks after the suspected violation. Thus, it would be useful to experimentally study ground potential distributions in the vicinity of nuclear explosions for long periods afterward. Laboratory measurements of electrofiltration potentials should also be made under both transient and steady state conditions.

SECTION 5
TREATY STRATEGY CONSIDERATIONS

5.1 INTRODUCTION

Up to this point, we have concerned ourselves with questions of technique, i.e., individual methods which can be used to monitor PNE's. We now move on to consider the more general question of how they can be combined amongst themselves and with treaty provisions to provide the most effective coverage for a given level of acceptable risk. We say "consider the question" because that is all that we can do. The writers of this report are not in a position to answer some of the most basic questions involved with treaty negotiations and national security. We cannot, for example, define "acceptable risk." Further, since our effort has been primarily a technical one, very little time has been devoted to the more general problems. These problems must be addressed at some point, however, and we can, at least, outline the rationale that should, ideally, be used.

The present PNE Treaty (PNET) was designed to be compatable with the Threshold Test Ban Treaty (TTBT), which limits yields of nuclear explosions to less than 150 KT (see Section 2). The rational that went into designing such a PNET is largely dependent upon the rational that went into the TTBT, or more specifically, the choice of a given yield as an upper limit for nuclear testing. One could argue that a treaty designed to limit new weapons development or nuclear effects testing, if it had any yield limit, would have a lower limit for testing rather than an upper limit. In any case, the present PNET was designed around artificially

imposed and easily defined conditions, an upper limit for testing yields, and therefore is oriented toward insuring that yield limits are not exceeded. A PNET associated with a Comprehensive Test Ban Treaty (CTBT), which allows no testing, should be designed around more basic premises and should be much stricter in the allowed verification procedures. The entire nature of the treaty would be different and not simply an extension of the present PNET. In a nutshell, the differences between the two can be stated as follows. The PNET associated with a TTBT is designed to help ensure that no nonpeaceful advantage can be gained from a PNE that could not be gained from a nuclear test of over 150 KT; the PNET associated with a CTBT should be designed to help ensure that no nonpeaceful advantage can be gained from a PNE. The latter purpose is essentially impossible to fulfill.

The discussion which follows will be oriented toward the CTBT/PNET.

5.2 SUMMARY OF PRESENT PNE TREATY

Tables 5-1 - 5-3 present a summary of the provisions of the present draft PNE Treaty which are relevant to the following discussion. Table 5-1 lists the types of information that must be supplied by the party conducting the explosion to the other party of the treaty. The information becomes increasingly detailed as the yield of the explosion, or the aggregate yield of the group of explosions approaches 150 KT. The information is clearly to aid teleseismic networks determine yield, and this must be determined with greater accuracy as the yield approaches the magic 150 KT mark after which on-site verification is allowed. Above 100 KT, information is required to be given which would appear to aid satellite reconnaissance.

Table 5-2 summarizes the allowed verification procedures; Table 5-3 details the yield measurement aspect of the verification. This

Table 5-1. Information to be furnished by party conducting the PNE.

For Aggregate Yield Exceeding (KT)	Information Furnished
0	1. Purpose of PNE 2. Location 3. Rock Type 4. Technological Features
50	1. Number of Explosives; Yield, Relative Location, Depth of Each Explosive; Time Intervals. 2. Geological Information Affecting Yield
75	1. Detailed Geological Information Including Physical Parameters of Rock within Spherical Volume Defined by a Radius Equal to 30 Times the Cube Root of the Yield for Each Emplacement.
100	1. Locations and Purposes of Facilities Associated with Explosion. 2. Emplacement Date of Each Explosive 3. Topographic Plan of Area

Table 5-2. Allowed PNE examination and verification procedures.

For Aggregate Yield Exceeding (KT)	Allowed Procedures
150	1. Confirmation that Local Circumstances (including Facilities and Installations) are Consistant with Stated Peaceful Purposes. 2. Confirmation of Geological Data (Rock Samples, Emplacement Hole Inspection, etc.) 3. Observation of Emplacement, Confirmation of Emplacement Depth, Observation of Stemming. 4. Observation of Entrance to Emplacement Hole from Time of Emplacement to Time Personnel are Withdrawn for Detonation. 5. Observation of Explosion. 6. Yield Measurement for Each Explosive (SLIFER)
500	7. Local Seismic Network May Be Used.

Table 5-3. Information to be supplied to aid in yield determination. Restrictions imposed on measurement and canister.

1. Determination of yield of each explosion to be based on measurements of the velocity of propagation of the hydrodynamic shock.

2. Information to be supplied:

   a. Length of each canister in which explosive is to be contained; dimensions of tube or other device used to emplace canister; cross-sectional dimensions of emplacement hole.

   b. Description of stemming materials.

   c. Coordinates of the explosive within emplacement hole, the entrance of the emplacement hole, the point of emplacement hole farthest from entrance, location of hole at 200 meter intervals, location of known voids larger than one cubic meter.

3. Portion of electrical equipment, used to measure yield, farthest from entrance to emplacement hole is to be placed at a distance from the bottom of the canister containing the explosive equal to 3.5 (3) times the cube root of the yield, in kilotons, when the yield is less (greater) than 20 kilotons.

   a. Canister containing explosive to be no longer than 10 meters.

   b. Data on density distribution within any other canister with cross-sectional area greater than 10 square centimeters is to be provided. Access to confirm such data is to be provided.

4. Explosives in separate emplacement holes shall be placed such that the distance between the explosive and any portion of the equipment measuring yield of any other explosive in the group shall not be less than 10 times the cube root of the larger yield. There will be a time interval, measured in milliseconds, between explosions which does not exceed one-sixth the difference between the actual and minimum distances.

5. Explosives in a common emplacement hole shall be not less than 10 times the cube root of the yield of the larger explosive and the explosives shall be detonated in sequential order, beginning with the explosive farthest from the entrance of the emplacement hole, with the individual detonations separated by time intervals, in milliseconds, of not less than one times the cube root of the yield of the largest explosive in this emplacement hole.

information is presented to indicate the type of precedents which have been set and which provide a reference point for reality when we discuss PNE treaties ideally.

5.3 SOME CONSIDERATIONS FOR A "REASONABLY" IDEAL PNE TREATY

In this section we will attempt to construct an ideal PNE treaty from first principles. It will rapidly be seen that the idealism required is so great that conditions will need to be artificially imposed in order to make the exercise useful. For example, a PNE treaty and monitoring procedures could be greatly simplified if visual inspection of the internal design of the explosive were to be allowed. Provision for such inspection would be a part of an ideal treaty. However, one cannot reasonably expect that, in the near future, either the Soviet Union or the United States will allow the other side to learn the secrets of their nuclear explosive techniques. The purpose of this exercise is to ask the questions that should be asked during the drafting of a treaty and, when possible, to supply one or more answers. This process is expedited by not limiting ourselves to conditions which can be ideally fulfilled, e.g., by anticipating what the Soviets will or will not allow. However, by stopping at ideal solutions, such as visual inspection, we would be bypassing several important considerations. Therefore, the idealism must be tempered by a certain amount of "reasonableness," and this is a highly subjective decision.

The first question that should be asked is "What do we hope to accomplish with a PNE treaty?" This was discussed in the introduction, and the answer depends upon the nature of any test ban treaties which are in effect at the time the PNE treaty is in effect. In general, one would desire treaty conditions which would prevent the use of a peaceful nuclear explosion to gain any nonpeaceful advantage that otherwise could not be gained because such a test was prohibited by treaty.

For our purposes, we will assume that a Comprehensive Test Ban Treaty (CTBT) is in effect. Therefore, ideally, the PNET would prevent any nonpeaceful advantage at all, an unenviable task at best.*

At this point, one must ask, "What is a peaceful nuclear explosion?" and "What are the nonpeaceful advantages that could be gained from a PNE?" For those who think in terms of bombs, the answer to the first question may be something simple, such as "the situation in which a nuclear explosive is used in a peaceful construction project and no military testing is being performed simultaneously," i.e., they would think in terms of big explosions and large amounts of dirt moving. For treaty negotiators, who have to write something on paper which their country can live with for many years, the answers to such questions are a little more subtle. For example, one method being developed for fusion power generation involves the explosion of tiny deuterium pellets. Presumably, as the process is perfected, explosion yields will increase and reasonable amounts of radiation will become available for some types of nuclear effects testing. How does this type of activity fit into PNE treaty considerations? How does one write a treaty such that nuclear effects testing cannot be conducted and yet the other party cannot legally demand an observer at every deuterium pellet explosion?

The question of nonmilitary advantage also has its subtleties. Nuclear weapons tests are usually performed for one of three reasons: (1) checking the nuclear weapon stockpile, i.e., seeing if the weapons are still up to par after a period of inevitable deterioration, (2) testing new weapons system designs, and (3) nuclear effects testing, i.e., testing the response of a system to nuclear radiation or performing

* We have chosen to use the very general term "nonpeaceful." More restrictive terms, such as "weapons related" or "military" could have been used, thus limiting the scope of the discussion somewhat.

experiments against which theory can be tested. Another type of nonpeaceful use of a nuclear explosive would involve (4) its use in a militarily beneficial construction or environment alteration program. How detailed should a treaty be in defining what can and cannot be called a PNE? At the present time it has been agreed that the PNE Treaty will govern all nuclear explosions which occur outside the weapon test sites specified in the threshold test ban treaty, but there is no specification as to what constitutes an explosion for peaceful purposes. Recall that the treaty only considers explosions of over 150 KT for verification purposes so that subtleties such as the pellet fusion explosion do not enter. Neither does the question of whether the treaty should cover explosions which are so small that they could not be detected by national technical means, e.g., teleseismic arrays. Ideally, a treaty would cover all nuclear yields, but is it realistic to conclude any treaty which depends on the party who violates it to tell you he violated it? Practical considerations may therefore place a lower limit on the yield which is governed by a PNET, such as some yield for which it is more practical to use chemical explosives than nuclear explosives in an earth moving project. This would simultaneously remove the need to consider the pellet question.

Similarly, it may expedite matters to ignore the fourth type of nonpeaceful advantage listed above and restrict the purpose of the PNET to hindering nuclear weapons systems development rather than to eliminate nonpeaceful advantages in general. Questions of militarily advantageous construction projects and environment alteration can be left to other treaty negotiations. The scope of the remaining discussion within this section will be thus limited in order to simplify matters.

Having defined a PNE and the military advantages one could gain through the use of a PNE, one must ask of each advantage "How much do I care if the other party gains this advantage and in what way do I care?" The more we care, the more restrictive the treaty and verification/monitoring

processes must be, i.e., the more intrusive and difficult they become. For illustrative purposes, we will confine our attention to the first three advantages listed above: stockpile check, new design testing, and nuclear effects testing. The stockpile check and new design test could be more easily inhibited if visual inspection of the explosive design were allowed. This will not likely happen. Even if it did, the possibility of such tests could not be eliminated in this manner since one could conduct a simple go/no go test by hiding the explosion in a group of other explosions.

The stockpile check is one potentially illegal test that probably will be difficult to eliminate for another very practical reason, namely, what is the source of the explosives used for PNE's? The best source in terms of explosives already available, is the weapons stockpile. In order to eliminate stockpile testing, one would have to develop specific peaceful explosives and ensure that these explosives were the only ones used. Again, this would be a difficult condition to impose upon a treaty signatory. It is possible that certain designs could be agreed upon by the parties involved. It is even possible that each party could manufacture the explosives used by the other party. Is it worth the effort?

The question of allowing a stockpile check is probably not as far reaching as the question of testing new designs. A treaty which allows the easy testing of new designs would not be a very effective one. This is also true of a treaty that did not guard against nuclear effects testing. With regard to weapons design testing, it is beneficial to ask "Why do we care if they develop new weapons designs?" We ask this question because, if we can address ourselves to restricting only certain classes of nuclear weapons designs, then it may be easier to guard against these classes than to guard against all weapons development. To do this we must look at the present trends in both the U.S. and the Soviet Union.* In general, the

* The authors of this report do not pretend to be experts in this area. Our analysis is only intended to serve as an example to others more competent to decide such matters. This line of reasoning was originally suggested by J. Hawxhurst, Mission Research Corporation, Santa Barbara.

types of weapons being developed involve relatively low yield and low weight-to-yield ratios for use in MIRV's and tactical weapons. The fact that the other party may be developing a 10 MT blockbuster is not as interesting as the possibility that he may be developing the capability to place ten 20 KT warheads within 1/2 km of their targets, independently, with a single carrier. On the other hand, there is a lower yield limit which is defined by the amount of damage which can be inflicted by conventional explosives or by the kinetic energy of a reentry vehicle made out of iron.* In addition, there is a lower limit which one could hope to identify by national technical means or by off-site observers on the other party's territory and it may be desirable to set a lower yield limit on this basis. Thus, as shown in Figure 5-1, there may be certain zones in which no restrictions are placed on the explosive. Within the restricted zones, only a certain discrete spectrum of explosives are allowed. Ideally, these would be useful for PNE's, but not for military systems. Also shown is a lower limit on the mass of the explosive. This point will be discussed later, but is related to the concept of using mass around the explosive to lower the X-ray temperature of the device and make it less useful for nuclear effects tests.

In addition to restrictions on yield and yield-to-weight, an observation of weapons development trends may enable one to fix other restrictions, such as X ray, neutron, or gamma ray efficiencies. This could be useful because, while the parties may not allow the spectra or effeciencies of their devices to be measured, they may allow a treaty provision which provides for the emplacement of a measuring device indicating that certain radiation levels have been exceeded.

A basic weapons test design can be relatively simple to conduct and can thus be performed with even strict treaty provisions. The most

* A mass of 1000 kg impacting at 10 km/sec would dissipate 5×10^{10} joules of energy, approximately equivalent to 10 tons of TNT.

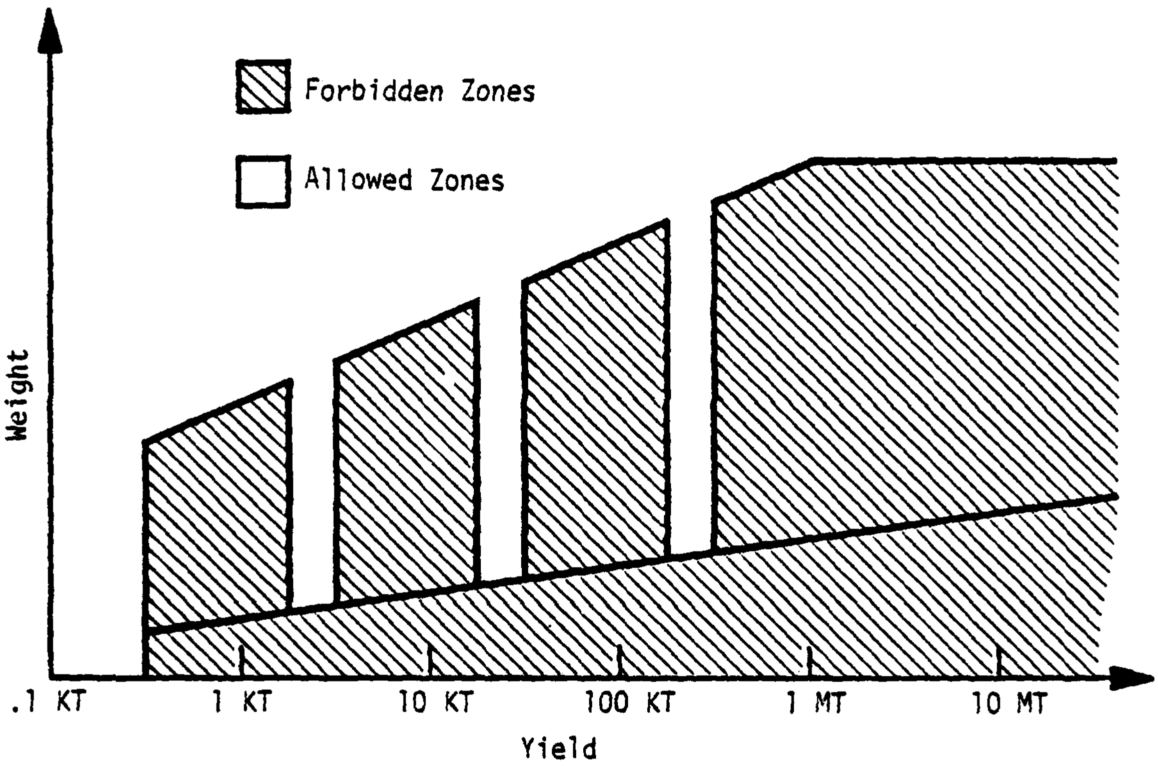

Figure 5-1. Qualitative example of the concept of restricting the yield-to-mass ratio of explosives allowed under a PNET, as well as the concept of an allowed spectrum within the forbidden range.

basic question is whether it went off, with what yield, and at what time. More sophisticated testing, such as certain types of radiation measurements, require more complicated instrumentation and, hence, are easier to hinder. As mentioned, putting mass around the explosive canister will change the X-ray spectrum (see Appendix B) and foil a measurement by equipment secreted down the emplacement tunnel. Similarly, restricting the size of the canister or canisters will hinder measurements made inside of them. For example, a canister on the order of ten meters length by three meters diameter would probably be large enough to allow any reasonable explosive design to be enclosed, but be small enough to preclude certain types of diagnostics. Note (Table 5-3) that a ten meter restriction is already included in the present treaty, although it appears to be there for the purpose of aiding the yield (SLIFER) measurement.

The concept of a fixed spectrum of weapons within the restricted yield range, introduced above (but not a new idea) serves the purpose of restricting changes in design. A new design can be introduced once for each yield. Some monitoring technique is then required to ensure that the design has not changed, since one could test dozens of designs for a given yield. Such a monitoring technique might be radio-chemical analysis.

Treaty provisions aimed at reducing the usefulness of a PNE in nuclear effects testing must concentrate on the area around the explosive. Nuclear effects testing requires considerable instrumentation and large volumes.* The equipment to be irradiated must be exposed to the radiation from the weapon and the radiation spectrum should not be altered substantially.

* Certain types of tests can be performed without large amounts of instrumentation, but the irradiated objects must later be recovered. See the second (classified) part of this report for more details on nuclear effects testing requirements.

The problem of guarding against nuclear effects testing on a declared explosion (as opposed to a hidden explosion) becomes one of guarding against cavities, chambers, and tunnels near the burst point. This can be performed most effectively by inspection techniques which are simply extensions of the ones presently allowed under the PNET. The massive canister concept, which changes the radiation spectrum is also an effective deterrent.

By making it difficult to perform a weapons or effects test on a declared PNE, the testor is forced to attempt to perform a test with an undeclared explosion hidden among the announced ones. For this reason, it is imperative that the treaty provide for monitoring procedures which can detect the presence of undeclared explosions. The local seismic system allowed for aggregate yields above 500 KT in the present treaty would be useful for explosions occurring within certain time and space intervals of each other. It may be possible to suppliment this system with an EMP monitoring system, which can resolve even closer intervals, or perhaps some other system can be used.

From the previous discussion, we can conclude that there are three tasks which can be performed by monitoring procedures: (1) device design confirmation, (2) cavity location, and (3) undeclared explosion detection. Before a treaty is written, the most efficient combination of available techniques for accomplishing these tasks must be decided upon and the treaty must be written in such a way as to optimize their effectiveness. The present treaty is an example. The treaty was written in such a way as to aid the teleseismic and SLIFER systems in operating with the highest accuracy.

SECTION 6
RECOMMENDATIONS

6.1 INTRODUCTION

This report presents the results of a preliminary study into certain aspects of a Peaceful Nuclear Explosion Treaty (PNET). The purpose of the study was to point out areas which should be explored in preparation for future treaty negotiations. Emphasis was placed on the possibilities of using new monitoring techniques, with particular emphasis on studying the feasibility of an EMP monitoring system.

In preparation for these studies, several ERDA related organizations were visited in order to review current nuclear test procedures and to attempt to learn of, or devise ways in which testing could be performed under the nonideal conditions of an illegal test disguised as a PNE. The results of some of these discussions and studies are presented in Part 2 of this report (limited distribution). Also included in Part 2 are further details concerning some of the monitoring techniques mentioned in Part 1 (Section 3). In addition, the authors met with several of the personnel involved with nuclear test ban treaty negotiations. The results of these discussions cannot be pinpointed in this report, but are reflected in the general tone of the report.

This study can be divided into roughly three elements:

1. New technology studies (Section 3).
2. EMP monitoring system studies (Section 4).

3. Monitoring technique integration and treaty strategy studies (Section 5).

Our findings and recommendations will be given for each element.

6.2 NEW TECHNOLOGY STUDIES

There are several new technologies which have been identified as deserving further investigation. We are sure there must be others. For example, it was noted in Section 5 that it might be useful to have radiation detectors which, for specific types of radiation, told if a certain dose level were exceeded. If such detectors do not already exist and if their existance would aid in negotiating a treaty, then an effort might be made to develop them.

The technology which holds the most promise for monitoring PNE's involve the monitoring of radiation leakages from the weapon canister. This will allow the detection of device design changes which might indicate a weapon development program under cover of a PNE program.

Other technologies which show promise for CTBT monitoring, but may be of highly limited value in a PNE are the infra-red and radar reflectivity techniques and the electrofiltration potential technique (see Section 4.3). These may be useful in finding the location of a clandestine explosion after it has been detected by some other means, but they do not show promise for being able to measure quantities of interest to PNE monitoring. The electrofiltration potential technique is not being actively studied at this time and we suggest that it be so. It may be more promising than the infrared and microwave techniques when surface measurements can be made.

6.3 EMP MONITORING SYSTEM STUDIES

The EMP data analysis performed to date indicates the strong possibility that an EMP monitoring system can be used to detect clandestine explosions hidden under cover of known peaceful explosions, even though the hidden explosion is not connected to cables. More experimental and theoretical work is required to prove this. Recommendations are given in Section 4.

6.4 MONITORING TECHNIQUE INTEGRATION AND TREATY STRATEGY STUDIES

In Section 5, several suggestions have been made for treaty provisions which would make difficult the use of a PNE for illegal purposes, e.g., weapon development. The important message is that the treaty provisions must be mated to the monitoring technique selection for either to be effective and that these must be negotiated as complete packages. Given a set of monitoring techniques and treaty provisions, one can predict beforehand the type of treaty violation that can occur and the probability of it occurring, and the difficulty of making it occur by design. A spectrum of negotiable packages with assigned risks can be assembled by technical experts and presented to the negotiators who would not be allowed to break up the packages without technical reexamination.

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APPENDIX

EFFECT OF HIGH ATOMIC WEIGHT SHIELDING ON THE RADIATING TEMPERATURE OF A DEVICE

To calculate the extent to which a layer of high atomic weight material reduces the effective radiating temperature of a nuclear device we make the following assumptions:

1. The layer is optically thick even if all the device yield is deposited in the shield material, i.e., $\tau \gg 1$, where τ is the number of Rosseland averaged radiation mean free paths in the layer.

2. The relation between the effective radiation temperature of the layer, T_{BR} and the internal (bulk) temperature of the layer, T is given by the following

$$T_{BR} = \left(\frac{1}{\tau}\right)^{1/4} T$$

(See Reference 1, p 164-165 for explanation.)

3. The Thomas-Fermi model for the high atomic weight atom is adequate to determine the opacity and equation of state for the layer material. (John C. Stewart, unpublished material, 1962.)

From assumption 3, the relation between temperature and energy Y deposited in a material of atomic weight A and mass M is

$$T = \left(\frac{7 \times 10^{12} A}{3 \times 49}\right)^{4/7} \left(\frac{Y \times 4 \times 10^{19}}{M}\right)^{4/7} \frac{49}{\alpha} \qquad \text{(B-1)}$$

T in electron volts

Y in kilotons

M in grams

A and α dimensionless

α is the natural logarithm of the free electron partition function, Γ. In the Thomas Fermi model

$$\Gamma = \frac{10^{-2} A (49)^{3/4}}{\alpha^{3/4} \rho} T^{3/4} \quad . \tag{B-2}$$

ρ is the material density, grams per cc.

Also from assumption 3, the Rosseland mean opacity κ can be written as

$$\kappa = \frac{10^{11} \alpha^{7/4} \rho}{(49)^{7/4} A^2 T^{5/4}} \tag{B-3}$$

κ in cm^2/gm .

If the shielding material of mass M is distributed around the device such that it has a surface area S cm^2 then

$$\tau = \frac{\kappa M}{S} \tag{B-4}$$

Now assumption 2 along with Equations 1, 2, 3, and 4 can be used to relate the maximum effective radiation temperature, yield of device, and mass of shielding material around the device. The procedure for solving these transcendental equations is as follows:

a. choose M, Y, A, S,

b. guess α (usually between 3-10)

c. calculate T from Equation 1

d. calculate a new α from Equation 2

e. recalculate T from Equation 1 using the new value for α

f. using this new T and α calculate κ from Equation 3

g. calculate τ from Equation 4. τ must be larger than unity

h. calculate T_{BR} from equation in assumption 2.

Illustrative example:

Choose $Y = 100$ KT, $A = 240$
$\rho = 20 \text{ g cm}^{-3}$, $M = 4 \times 10^5$ g, $S = 10^4 \text{ cm}^2$

Then we calculate:

$$T = 5700 \text{ eV}$$
$$\alpha \approx 6$$
$$\kappa = 18 \text{ cm}^2/\text{gm}$$
$$\tau = 710$$
$$T_{BR} = 1100 \text{ eV}$$

In other words, the addition of 400 kg of metal* around a 100 KT device to a thickness of 2 cm will reduce its radiation temperature from about 6 or 7 kilovolts to about 1 kilovolt. Furthermore, $T_{BR} \sim M^{-1}$, so increasing the mass to 800 kg should drop the radiation temperature to about 1/2 kilovolt.

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*Probably lead would be the best choice for a material. However, the product $T\alpha$ must be less than the K-shell ionization energy for the material chosen; for lead this is about 70 kilovolts. If $T\alpha$ exceeds this value, then the opacity of the shield falls dramatically and assumption 1 is no longer valid.

Reducing the effective radiation temperature also increases the duration of the radiation pulse. The amount of increase depends on how much the effective radiating area is increased by the addition of the shield material, as well as the optical depth of the shield material. The pulse width increase factor can be roughly written as

$$\frac{S'}{S} \tau$$

For the sample problem above the typical values for S', the radiation area without the shield, are a few hundred cm^2. From the calculations above where S was 10^4 cm^2 and τ was ~ 700, the ratio $\frac{S'}{S} \tau$ may be hardly changed at all; perhaps the pulse duration would be increased by a factor of 2. However, if S were taken to be much smaller than 10^4 cm^2, then significant increases to pulse duration could be achieved.

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